APRIL/MAY 2021 | SCIENTIFICAMERICAN.COM

SCIENTIFIC AMERICAN
Space & Physics

The Age of Perseverance

A NEW ROVER HAS LANDED ON MARS AND BEGINS A NEW ERA OF EXPLORATION ON THE RED PLANET

PLUS

TELESCOPES ON THE FAR SIDE OF THE MOON

HAVE WE BEEN VISITED BY ALIENS?

ANCIENT MASSIVE GALAXIES

WITH COVERAGE FROM nature

LIZ TORMES

Onward, Intrepid Rover

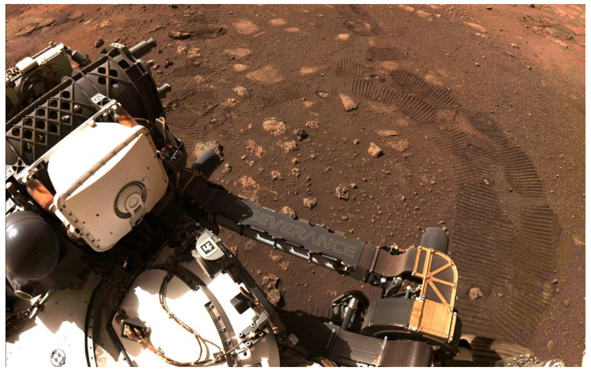
In 2008 an engineer friend of mine helped to design the sky crane that lowered the Curiosity rover from the hovering rocket to the surface of Mars. In commemoration, his signature was engraved on a small plaque on the device. Thirteen years later this past February, that same crane design helped to successfully land Perseverance in the Jezero Crater on the Red Planet. Our space and physics senior editor Lee Billings and journalist Jonathan O'Callaghan report on this remarkable achievement and detail the tall order of tasks ahead for the fifth robotic visitor to Mars (see "Perseverance Has Landed! Mars Rover Begins a New Era of Exploration" and "The First 100 Days on Mars: How NASA's Perseverance Rover Will Begin Its Mission").

This time Perseverance is bringing with it nearly 11 million names from Earth to our neighboring planet—each name stenciled on a silicon chip installed on the rover's body. Like scraps of paper folded inside bottles floating across the ocean, these little pieces of our humanity—our names—have been flung far from the surface of our home planet. Perhaps the goal is the same: to connect, even in a small way, with whatever is found on the other side. Godspeed, intrepid explorers!

Andrea Gawrylewski
Senior Editor, Collections
editors@sciam.com

Your Opinion Matters!

Help shape the future of this digital magazine. Let us know what you think of the stories within these pages by e-mailing us: editors@sciam.com.



On the Cover

This image was taken during the first drive of NASA's Perseverance rover on Mars on March 4, 2021. Perseverance landed on February 18, 2021, and the team has been spending the weeks since landing checking out the rover to prepare for surface operations. This image was taken by the rover's Navigation Cameras.

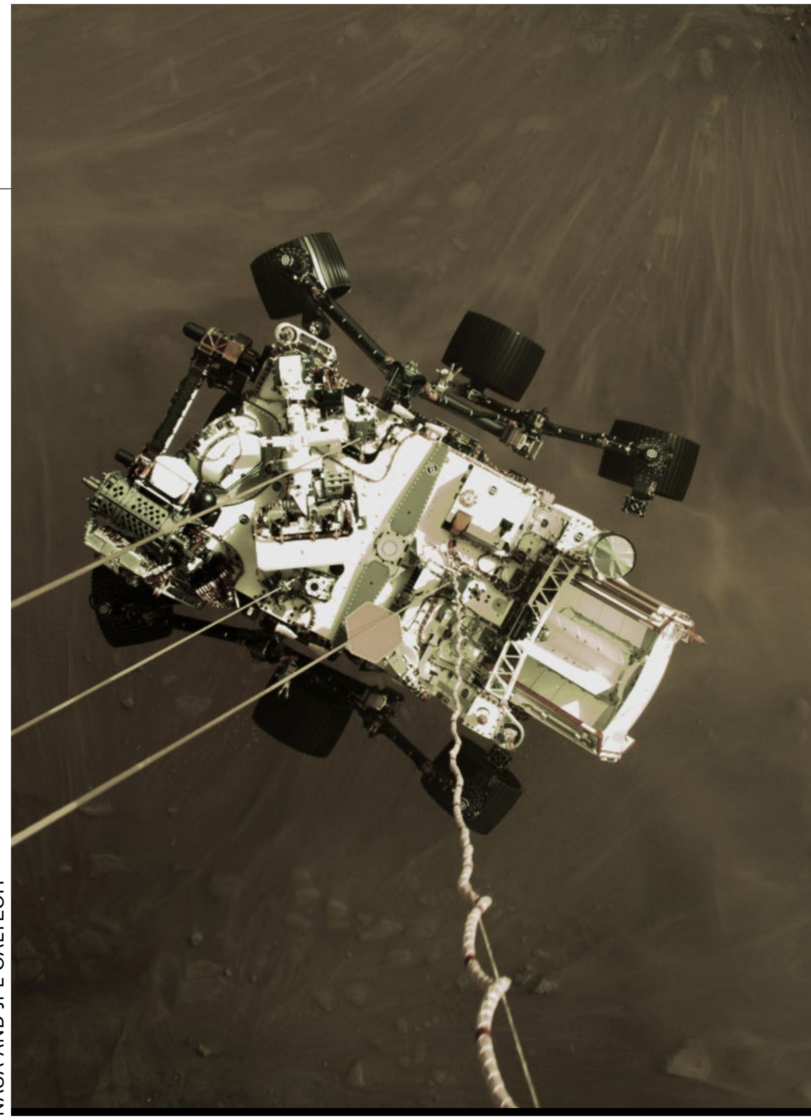
NASA AND JPL-CALTECH

WHAT'S INSIDE

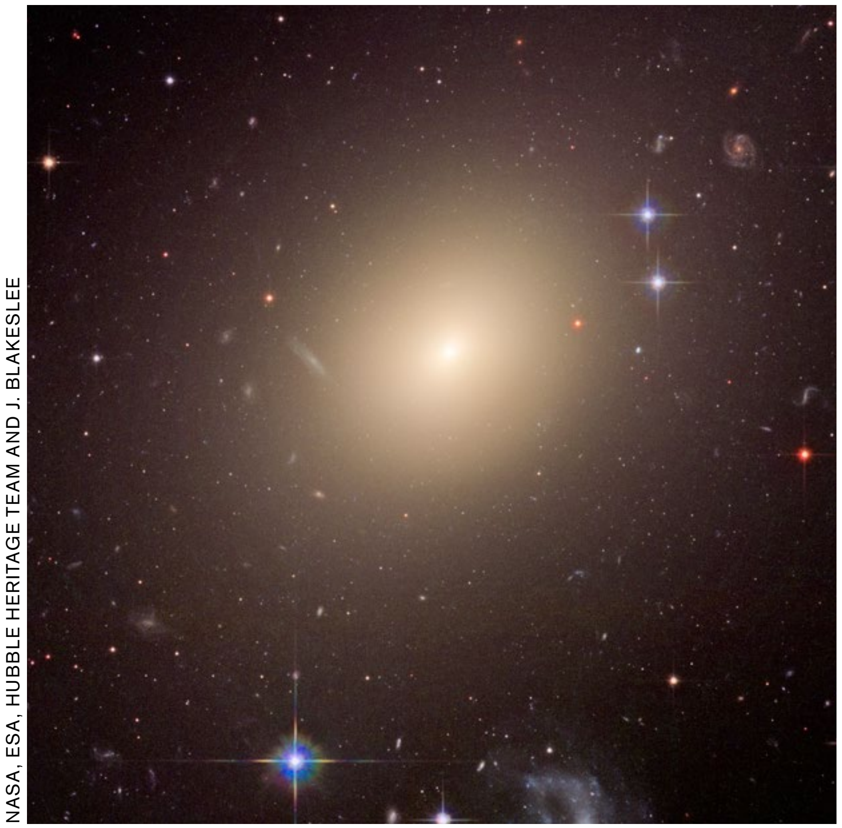
April–May 2021
Volume 4 • Number 2

NASA AND JPL-CALTECH

NEWS



NASA AND JPL-CALTECH



NASA, ESA, HUBBLE HERITAGE TEAM AND J. BLAKESLEE

FEATURES

OPINION

NEWS

Perseverance Has Landed! Mars Rover Begins a New Era of Exploration

NASA's latest mission to the Red Planet will seek out signs of ancient life, gather samples for return to Earth and even fly a first-of-its-kind interplanetary helicopter

Humanity's on-again, off-again exploration of Mars has lived through its latest make-or-break moment, and scientists around the world are breathing sighs of relief.

Shortly after 3:44 P.M. Eastern Standard Time February 18, 2021, a visitor from Earth fell from a clear, cold Martian sky into a 3.5-billion-year old, 50-kilome-

This high-resolution still image is part of a video taken by several cameras as NASA's Perseverance rover touched down on Mars on February 18, 2021. A camera onboard the descent stage captured this shot.

NASA AND JPL-CALTECH

ter-wide bowl of rock, dust and volcanic ash called Jezero Crater that once held a large lake. Seven minutes earlier it had touched the top of the planet's atmosphere at nearly 20,000 kilometers per hour, bleeding off most of its speed through friction, protected from the resulting fireball by a heat shield. A supersonic parachute the size of a Little League baseball field unfurled to slow it further, followed by a final computer-piloted descent on a robotic jetpack called a sky crane, which used a detachable tether to gently lower the visitor to rest on the crater floor. Far overhead, orbital spacecraft monitored its progress, awaiting the first signals confirming its successful landing, which, beamed earthward at the speed of light, would arrive at our planet some 11 minutes later.

At long last, NASA's Mars Perseverance Rover has arrived. Conceived a decade ago and distilled from the dreams of generations of scientists, the car-sized, nuclear-fueled rover launched in July 2020, months into a world-transforming pandemic, traveling nearly half a billion kilometers in seven months and surviving a high-tension seven-minute planetfall from space to reach Jezero Crater—where its real hard work will now begin.

Perseverance (or even just "Percy," for short) is meant to trundle across the terrain for at least a Martian year (two Earth years), following an ambitious to-do list. Explore the environment with rock-vaporizing lasers and ground-penetrating radar, and snap high-resolution panoramas, 3-D stereograms and microscopic close-ups with a suite of sophisticated cameras? Check. Listen to Martian soundscapes, and create weather reports with onboard sensors? Check. Test a device for manufacturing oxygen from the suffocatingly thin air, and launch Ingenuity, a first-of-its-kind four-bladed Marscopter on sorties through those alien skies? Check.

According to Matt Wallace, the project's deputy project manager at NASA's Jet Propulsion Laboratory (JPL) and a veteran of all previous Mars rover missions, those latter two tasks and Perseverance's overall complexity make it "the first one I think of as a human precursor mission." Scaled up, its oxygen-producing experiment, MOXIE, could provide breathable air and rocket fuel for future astronauts, who could also use more advanced Marscopters to scout out their surroundings.

But, truth be told, all of that is secondary or supplemental to Perseverance's true reason for being, which is to determine if life ever existed on Mars—and if it ever will.

PERSEVERANCE'S QUEST

"This rover is, at its heart, a robotic geologist and a mobile astrobiologist," said Lori Glaze, head of NASA's planetary science division, during a public presentation the day before the landing. "We're really going after the ability to identify which rocks might be most likely to have preserved the organic fingerprints of life in the past."

Since the dawn of the space age, the Red Planet has been the most prized target for astrobiological studies, being the closest remotely Earth-like body in the solar system. Although it is currently a cold, hostile desert of a world, billions of years ago it was warmer and wetter—presumably a perfectly fine place for the basics of biology to arise. But somehow, long ago the paths of Mars and Earth diverged, leaving only one planet teeming with life.

Seeing no sign of ancient life on Mars would bolster the case that Earth is indeed rather special, suggesting that despite almost identical initial conditions no wee beasties ever managed to emerge on our sister world. In contrast, finding an independent origin of life on Mars would be potent evidence for the mind-boggling notion that the universe is in some sense built for biology's blossoming. And while most scientists suspect fossilized microbes to be the most advanced organisms we could discover on the Red Planet, any extant life there—even if single-celled—would spur some to call for a planetary quarantine, to leave Mars to the Martians. A seemingly sterile planet would be, in some respects, the most promising scenario for eventual human exploration and even settlement there.

Perseverance promises to bring us closer to answers for these interlinked mysteries than any other mission in history. Not the least because of its landing site, Jezero Crater, which harbors one of the planet's largest ancient lake-and-delta systems and is filled with

sediments (and, just maybe, microfossils) washed in from the surrounding watershed.

Additionally, Jezero is sandwiched in space and time between two formative occurrences in Mars's history. It lies within Syrtis Major, a volcanic complex that formed about 3.8 billion years ago, which itself sits adjacent to the Isidis Planitia basin, a gargantuan impact crater that formed about 100 million years before Syrtis's first eruptions. The site "is bookended by these major planetary events.... We see their influence in the rocks around Jezero," said Katy Stack Morgan, Perseverance's deputy project scientist at JPL. At Jezero, she said, "we have this window into early solar system evolution and the period of time when life was emerging on Earth and might have been emerging on Mars as well."

SAMPLING ON THE SHOULDERS OF GIANTS

Of the nearly 50 spacecraft that have been sent to Mars since the 1960s, to date only five—all from NASA, including Perseverance—have successfully traveled across the surface (China's Tianwen-1 lander, slated to touch down in May of this year with a rover of its own, seeks to be the sixth). First came a tiny pathfinder, Sojourner, that in 1997 showed roving was possible. Next were the twin Mars Exploration Rovers, Spirit and Opportunity, that arrived in 2004 to "follow the water" and establish the local abundance of life's liquescent cornerstone. Those were followed by Perseverance's near clone and precursor, Curiosity, which reached the planet in 2012 to perform still ongoing investigations of its habitability. None, however, came anywhere close to doing what many earthbound experts believe to be the most crucial step in Mars exploration: Bringing modest, pristine pieces of the planet back to Earth, where researchers can study them for signs of biology using laboratory equipment that cannot fit into any conceivable rover.

"In my view, sample return from Mars is the planetary science endeavor of our generation," said Bobby Braun, director of planetary science at JPL. "It's the ambitious, challenging, scientifically compelling goal that—if we work together over timescales of decades—is just within our reach."

Unlike all its predecessors, Perseverance will be the opening shot in this audacious effort, a collaboration between NASA and the European Space Agency dubbed the "Mars Sample Return" (MSR) campaign.

THE INTERPLANETARY RELAY RACE BEGINS

The crux of Perseverance's MSR work will take place via a turret packed with cameras, spectroscopes and drilling equipment at the end of its two-meter-long robotic arm. Wallace and others have compared this rugged assemblage to a miniaturized chemistry lab and clean room mounted on a jackhammer, all operating near the limits of technological tolerance for the dust, radiation and wild swings in temperature that define the Martian surface environment. Mission scientists will use the turret to identify and retrieve material of astrobiological interest, filling up to 43 test tube–like containers that will then be cached for later pickup by subsequent follow-up missions now in development.

According to Stack Morgan, she and her colleagues are tentatively targeting several regions for prioritized sample-gathering, such as Jezero Crater's floor and rim, as well as the site's enormous delta and the margins of its ancient shoreline.

Now that Perseverance is safely on the surface, the clock is ticking. "We need to collect a lot of those samples very quickly," Wallace said, citing 20 samples in one Martian year as the mission's baseline goal. However many Perseverance collects, they all must be ready for eventual pickup by a tag-team duo—a Sample Retrieval Lander and an Earth Return Orbiter—that could launch later this decade. Working together like partners in a relay race, they could bring the baton—perhaps a half kilogram of precious specimens—across the terra firma finish line as early as 2031.

"The science that Perseverance will do is going to inform our world for decades," Braun said. "There are scientists in schools today and perhaps not even born yet who will benefit from what's about to happen.... Perseverance is the first step that initiates the sample-return campaign, but already in the U.S. and across Europe we're working on the next two missions."

—Lee Billings

The First 100 Days on Mars: How NASA's Perseverance Rover Will Begin Its Mission

The space agency's latest rover set down on February 18, 2021. Here is the agenda for its initial months

On a space mission, timing is everything. An intricate choreography of commands and actions is required to make any such mission a success and none more so than an escapade on the surface of another world. On February 18, NASA was set for another delicate dance of interplanetary chronology when its Perseverance rover touched down on Mars—the successor to its aesthetically identical sibling, Curiosity, which landed in 2012. This time around, the mission is conducting a search for past life on Mars, alongside other exciting experiments.

The 1,025-kilogram rover is powered by a radioisotope thermoelectric generator, fueled by heat from decaying plutonium, which

This is the first high-resolution, color image to be sent back by the Hazard Cameras (Hazcams) on the underside of NASA's Perseverance Mars rover after its landing on February 18, 2021.

NASA AND JPL-CALTECH

should help it avoid a dust-laden fate such as prematurely ended the missions of its solar-powered predecessors Opportunity and Spirit; however, getting up and running as soon as possible after the landing is still crucial. The rover has an ambitious amount of science to conduct in its primary mission lasting one Martian year (two Earth years). And although its mission is likely to be extended, given the overwhelming richness of its landing site in the ancient Martian river delta within Jezero Crater, scientists are eager to get the ball rolling sooner rather than later.

Before they could get down to that urgent business, however, Perseverance first needed to endure its autonomous seven-minute descent to the surface—known as the "seven minutes of terror"—and then to check that its vital organs were in working order as well as launch a first-of-its kind attempt at aerial flight.

Suffice to say, the busy rover's schedule is positively jam-packed. Interplanetary mission timings are always subject to change depending on how things progress, of course, but a time line is in place for Perseverance's first 100 days on Mars. (Note: a day on Mars is about 40 minutes longer than a day on Earth.)

Here is how it is all set to play out.

DAYS 1 TO 10

The very first thing Perseverance will do after landing is to fire some pyrotechnic devices, releasing the covers on cameras onboard the rover. It will then take images in front and behind the rover and send those back to Earth via NASA's orbiting Mars Odyssey spacecraft and Europe's Trace Gas Orbiter. After that? A quick nap, of course, "to recharge the batteries until the next day on Mars," says Jennifer Trosper, deputy project manager for the mission at NASA's Jet Propulsion Laboratory (JPL).

Over the first few days, Perseverance will go through a number of important tasks to ensure it is up and running smoothly. It will confirm its exact location on Mars, while the team will "try to establish the vehicle's base functions—power, thermal, and communications," Trosper says. "Because if any of those base functions aren't working, then the vehicle can be in [danger] very quickly."

It will also use the sun's overhead position to figure out where exactly Earth is in the sky for direct communications and then run through checks of its instruments and systems—while continuing to beam back images of its surroundings, too.

"It'll take us about four or five days to get all that done," Trosper says. The next five days, meanwhile, will be spent transitioning from the software the rover used to land to the software it needs to operate on the surface. The rover will then test out its robotic arm, which will be used to collect and store samples on the surface, and will also take its very first "steps," performing a short drive on its six rugged wheels. While all this is going on, however, another team will be poring through images of the landing site, getting ready for a major test—the first flight on Mars.

DAYS 11 TO 60

Tucked into the belly of Perseverance is a small 0.5-meter-tall stowaway called Ingenuity. This "Mars helicopter," with four spinning blades, will attempt powered aerodynamic flight through the skies of another world for the first time, a technological demonstration that could be a prelude to flying reconnaissance drones on future human missions. Ingenuity's flights will require Perseverance to find a flat location, somewhere picked by the helicopter team within a 10-day drive of the landing site, Trosper says, or up to one kilometer away—with the rover able to travel about 100 meters a day.

Once it finds that site, the deployment will be slow. Ingenuity is stored sideways under Perseverance, so it must be slowly rotated and lowered to the surface. The legs must be unfolded with the help of springs, while the helicopter must receive a final jolt of charge from Perseverance before it switches to its own onboard solar-powered battery. Then, once all checks have been complete and everything is ready, it will be gently dropped to the surface. In theory, this whole process—apart from the battery charge—takes just minutes. But the engineers will progress extremely carefully, taking multiple pictures along the way, meaning the entire deployment will actually be "in the range of a Mars week," says Joshua Ravich, the helicopter's mechanical engineering lead at JPL.

From here, the helicopter's mission begins. It has a 30-day window to conduct up to five autonomous flights on Mars, each lasting up to 90

seconds. The flights will begin low and short but should eventually progress to higher altitudes and distances of potentially a few hundred meters. "Flight number five could be something as complex as liftoff, fly some distance, pick a new landing site by itself and land at this site," Ravich says. Only one flight can be attempted per day at most, with the helicopter charging in between. Watching will be Perseverance, taking images and possibly even video of the flights.

DAYS 60 TO 100

There is some margin for error in these early activities, with day 60 being the earliest and day 100 the latest they might finish. Either way, the conclusion of the helicopter test flights—five flights or 30 days, whichever comes first—will mean the initial phase of the mission is over. Now the move toward the rover's primary science objectives will begin. "The engineers turn the keys of the rover over to the science team," says Katie Stack Morgan, deputy project scientist on Perseverance. "Once the helicopter is done, many of our science instruments will be ready to go."

This photograph was selected by public vote and featured as "Image of the Week" for week 4 (March 7–13, 2021) of the Perseverance rover mission on Mars. NASA's Mars Perseverance rover acquired this image using its onboard Right Navigation Camera (Navcam). The camera is located high on the rover's mast and aids in driving.

NASA AND JPL-CALTECH

The science team will have picked a first site to send the rover to in the mission's initial weeks on Mars. "Depending on where we land, we have a menu [of sites] to choose from," Morgan says. "What I anticipate we might be looking at is planning a science investigation on the crater floor before our investigation of the [river] delta, because it might be a volcanic rock, and volcanic rocks are really good for getting absolute age dates from," giving a useful temporal baseline for any future samples collected by the rover.

In the days thereafter, Perseverance will potentially scoop its first samples on Mars and leave its first cigar-sized tube on the surface—small caches designed to be picked up by a future sample-return mission, to be brought back to Earth. Its MOXIE instrument, a technology demonstrator that will pluck carbon dioxide from

the Martian atmosphere for chemical transformation into breathable oxygen, will likely be up and running, as will MEDA—a Martian weather instrument—and RIMFAX, which will use radar to look for water ice underground.

It is a mission that will begin unlike any other, given the helicopter demonstration in its early phase. But once that is done, and the rover has gone through its checks to confirm it is properly functioning, its primary mission on Mars will be truly underway. After its first 100 days on Mars, possibly sometime in June, the rover will be ready to conduct one of the most exciting searches for life on Mars to date. At this point it's "full steam ahead," Trosper says—and who knows what secrets might lie in store?

—Jonathan O'Callaghan

Editor's Note: In the month since it landed, Perseverance has already beamed back nearly 13,000 pictures, conducted its first drive, recorded the sounds of Martian winds, zapped nearby rocks with lasers, and prepped Ingenuity for flight. Even so, the mission's defining moment—its inaugural collection of samples for return to Earth—is yet to come.

Galaxy-Size Gravitational-Wave Detector Hints at Exotic Physics

Recent results from a pulsar timing array, which uses dead stars to hunt for gravitational waves, has scientists speculating about cosmic strings and primordial black holes

Representative illustration of Earth embedded in spacetime is deformed by the background gravitational waves and its effects on radio signals coming from observed pulsars.

TONIA KLEIN NANOGRAV

The fabric of spacetime may be frothing with gigantic gravitational waves, and the possibility has sent physicists into a tizzy. A potential signal seen in the light from dead stellar cores known as pulsars has driven a flurry of theoretical papers speculating about exotic explanations.

The most mundane, yet still quite sensational, possibility is that researchers working with the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), which uses the galaxy as a colossal gravitational-wave detector, have finally seen a long-sought background signature produced when supermassive black holes crash and merge throughout the universe. Another interpretation would have it originating from a vibrating network of high-energy cosmic strings that could provide scientists with extremely detailed information about the fundamental constituents of physical reality. A third possibility posits that the collaboration has spotted the creation of countless

small black holes at the dawn of time, which could themselves account for the mysterious substance known as dark matter.

"People have been making predictions about cosmic strings and primordial black holes for years, and now, finally, we have a signal," says Chiara Mingarelli, an astrophysicist at the University of Connecticut and a member of the NANOGrav team. "We're not sure what is generating this signal, but a lot of people are really, really excited."

The physics community has learned a great deal about the universe from massive terrestrial gravitational-wave experiments such as the Laser Interferometer Gravitational-wave Observatory (LIGO) and its European counterpart Virgo. But just as electromagnetic waves come in a spectrum ranging from squashed gamma rays to lengthy radio waves, gravitational waves run the gamut from the tiny vibrations in spacetime made when sun-size black holes merge to those with wavelengths measurable in light-years that can take decades to pass by our planet. The collective, overlapping cacophonies from those larger waves, thought to be produced when behemoth black holes lurking in the centers of galaxies collide, are what the NANOGrav collaboration has been working to capture.

It does so by focusing on objects known as millisecond pulsars, which arise when massive stars explode as supernovae and leave behind their rapidly spinning remnant hearts. A pulsar's strong magnetic field can create a beam of radiation that swings around, repeatedly sweeping past Earth with a regularity that rivals the accuracy of atomic clocks. Should a distortion in the fabric of spacetime come between our planet and a pulsar, it can cause this signal to arrive slightly earlier or later than expected. Were a telescope to see one such offset, it probably would not mean much. But NANOGrav has been monitoring the light from 45 pulsars scattered over thousands of light-years for more than 12.5 years, looking for correlations between their arrival times that could indicate the presence of gravitational waves.

Last September the collaboration posted a paper on the preprint server arXiv.org, which hosts scientific articles that have yet to go through peer review, showing that its monitored pulsars all displayed similar blips. (The paper has since been peer-reviewed and published.) The chances of this happening are between 1,000 and 10,000 to one, Mingarelli says. As a group, NANOGrav is cautious and has refrained from claiming it has seen a gravitational-wave signal, which requires observing highly specific correlations among its pulsar signals' arrival times. That did not stop other scientists from jumping on the data.

"If we detected cosmic strings, it would be the detection of my lifetime. It would be more important than the Higgs boson, probably more than gravitational waves themselves."
—Eugene Lim

Marek Lewicki, a theoretical physicist at the University of Warsaw in Poland, recalls that the NANOGrav study appeared early on a Friday morning and that by 10 A.M., his collaborator John Ellis of King's College London had spotted it. Although the usual explanation for such a signal is the supermassive black hole gravitational-wave background, Lewicki knew that another possible culprit was cosmic strings, and he began running models to see if this option could account for the data. "By Saturday, it was pretty clear it was a good fit," he says.

Researchers like cosmic strings because they directly connect cosmological events to high-energy particle physics. Shortly after the big bang, three of the four known forces—electromagnetism and the strong and weak nuclear forces—would have been smushed together into one superforce. When the strong nuclear force dissociated itself, the universe would have gone through what is known as a phase change, much like water freezing into ice. And just as a frozen lake often contains long cracks created when its bulk solidifies, the visible cosmos would become strewn with enormous nearly one-dimensional tubes of energy crisscrossing its length. Such objects would be tense

like piano strings and could vibrate out gravitational waves that would look like the signal NANOGrav had picked up.

Because these cosmic strings originated near the beginning of time, they would carry information about processes such as cosmic inflation, during which the universe is thought to have rapidly ballooned by mind-boggling factors, as well as the creation of different particles at different extreme temperatures, says Kai Schmitz, a theoretical physicist at CERN near Geneva. Information from such conditions, which would be impossible to create in particle accelerators such as the Large Hadron Collider, could help researchers produce a grand unified theory connecting most known particles and forces that would supersede the current Standard Model. Along with two collaborators, Schmitz published a paper in *Physical Review Letters* (*PRL*) outlining how cosmic strings could account for the NANOGrav data on January 28, the same day a similar article by Lewicki and Ellis appeared.

"If we detected cosmic strings, it would be the detection of my lifetime," says Eugene Lim, a cosmologist also at King's College London. "It would be more important than the Higgs boson, probably more than gravitational waves themselves."

For this reason, Lim, who was not a co-author on either paper, stresses that such concepts need to be considered with an abundance of restraint. The NANOGrav collaboration still needs to confirm that it is in fact seeing gravitational waves. And the shape of those gravitational waves' spectrum has yet to be traced out and found to conform to the cosmic string interpretation, each of which is likely to take years, he adds.

Meanwhile another contingent of the physics community has suggested that the signal could originate from entities known as primordial black holes. Unlike regular black holes, which are born when gigantic stars die, these would form in the early universe, when matter and energy were nonuniformly scattered through the cosmos as a consequence of processes that occurred at the end of inflation. Certain overdense areas could collapse under their own weight, generating black holes in a variety of sizes. Observations from LIGO and Virgo that could indicate mergers between primordial black holes have already planted the idea in many researchers' minds that these strange objects are more than speculative fictions. Certain theorists like them because as entities that give off no light, they could account for some or even all of the dark matter in the universe.

"This is an economical explanation," says Antonio Riotto, an astroparticle cosmologist at the University of Geneva, because they do not require theorizing about exotic undetected particles such as WIMPs or axions, which have thus far dominated physicists' musings about dark matter.

Along with two co-authors, Riotto has written a third paper appearing in *PRL* showing how the NANOGrav signal could be accounted for by a multitude of black holes the size of asteroids being created shortly after the big bang, producing a gravitational-wave relic that would travel to us in the modern day. According to the researchers' model, these miniature primordial black holes could make up to 100 percent of the dark matter in the universe.

Yet this possibility, too, needs to be approached carefully, says Juan García-Bellido, a theoretical physicist at the Autonomous University of Madrid, who was not involved in the work. While the NANOGrav data contain hints, it does not quite show the specific correlated pattern that would indicate gravitational waves, and much of the speculation seems premature to him. "I'm the first to hope for primordial black holes," he says. "But I'm afraid it's not yet there."

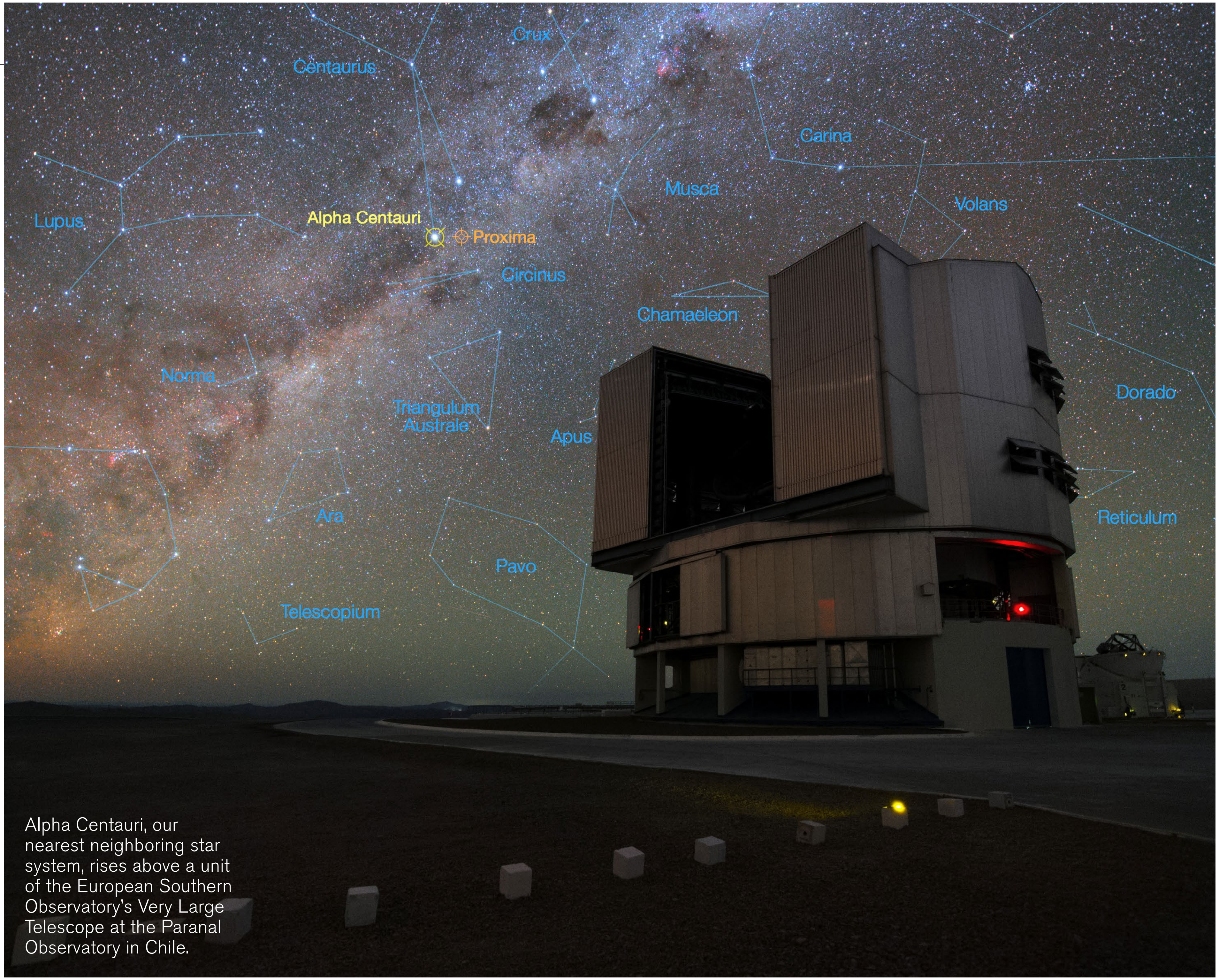
Nevertheless, the burst of theoretical activity shows how seriously physicists are taking these results. NANOGrav researchers have another two and a half years of pulsar data they are combing through, which could help distinguish whether some or a combination of all these explanations might be viable. They are also working with international collaborators such as the European Pulsar Timing Array (EPTA) and Parkes Pulsar Timing Array (PPTA) in Australia, each of which has observations of other pulsars that could get them closer to spotting the needed correlations to finally pin down the gravitational-wave background—a process that should be underway before the end of this year.

"I would be shocked if we didn't see a signal when we combined all of our data," Mingarelli says.

—*Adam Mann*

Is It a Planet? Astronomers Spy Promising Potential World around Alpha Centauri

The candidate could be a "warm Neptune" or a mirage. Either way, it signals the dawn of a revolution in astronomy



Alpha Centauri, our nearest neighboring star system, rises above a unit of the European Southern Observatory's Very Large Telescope at the Paranal Observatory in Chile.

Y. BELETSKY (LCO)/ESO

For the first time ever, astronomers may have glimpsed light from a world in a life-friendly orbit around another star.

The planet candidate remains unverified and formally unnamed, little more than a small clump of pixels on a computer screen, a potential signal surfacing from a sea of background noise. If proved genuine, the newly reported find would in most respects not be particularly remarkable: a "warm Neptune" estimated to be five to seven times larger than Earth, the sort of world that galactic census takers such as NASA's Kepler and Transiting Exoplanet Survey Satellite missions have revealed to be common throughout the Milky Way. But even though it would be shrouded in gas and essentially bereft of any surface to stand on, its distance from its star would place it in the so-called habitable zone, where liquid water could exist. No other planet has been directly seen in this starlight-drenched region around any other star because of the associated glare. And this world's celestial coordinates would be straight out of astronomers' wildest

dreams—it would orbit a near twin of the sun called Alpha Centauri A, which also happens to be a member of a triple-star system that, at just shy of 4.5 light-years away, is the closest one to our own.

Because of its proximity, the system's other members—a slightly smaller sunlike star called Alpha Centauri B, and the diminutive red dwarf star Proxima Centauri—are also high-priority targets for astronomers, who have already indirectly detected the presence of two worlds around Proxima (including one that is likely rocky and within that star's habitable zone). Whether looking for real estate across town or around another star, location really is everything.

The Centauri system is so close that it offers a unique front-row seat for scientists seeking to study the atmospheres and surfaces of any worlds that exist there, especially to seek out possible signs of life. And astronomers long ago learned that planets are, in some respects, like household pests: where one is seen, others are likely to be found. Which is why, as tentative as they may be, the burgeoning crop of Centauri worlds hints at discoveries that could profoundly transform views of our place in the universe.

The findings were reported in February in the journal *Nature Communications.* They come from an international consortium of planet hunters called Breakthrough Watch, via the inaugural science run of a one-of-a-kind "direct imaging" instrument called NEAR (New Earths in the AlphaCen Region), which operates on the European Southern Observatory's (ESO) Very Large Telescope (VLT) in Chile. The effort is named for its chief funding organization, Breakthrough Initiatives—the brainchild of Silicon Valley billionaire Yuri Milner, who also sponsors related projects to search the heavens for signs of alien civilizations and to send pint-sized interstellar probes to the Alpha Centauri system.

"Alpha Centauri presents us with a magical opportunity because there is no better place in the sky to try to directly image small, potentially habitable planets," says study co-author Pete Klupar, Breakthrough Initiatives' chief engineer. "This was in some sense low-hanging fruit—for just $3 million, we were with our international partners able to build an instrument to take advantage of ESO's billions of dollars invested in its telescopes. But it's also like going after a needle in a haystack, which is why no one has ever done this before. Governments tend to build survey instruments, to look at large numbers of stars and guarantee a return on investment, whereas NEAR was purpose-built to just do this one, risky thing."

"When we collaborate on a global scale, we discover new worlds, and we keep advancing," Milner says. "The identification of a candidate habitable-zone planet in our celestial backyard will continue to power our curiosity."

THE BLIP

The candidate's tantalizing signal emerged from 100 hours of observations on the VLT, stretched across a total of 10 nights in the spring of 2019. By June of that year, as the Breakthrough Watch team members sifted through their observations, they began to realize they might have found something. Kevin Wagner, the study's lead author and a postdoctoral Sagan Fellow at the University of Arizona, first saw the telltale evidence of a planetlike blip cresting far above NEAR's instrumental noise. It happened while he was remotely processing a batch of data during a family vacation in Lake Jocassee, S.C. Measuring its brightness and sandwiching it between limits on planet masses and sizes calculated in previous studies by other groups, the Breakthrough Watch team estimated that—if the blip were indeed a planet—it would most likely be somewhere between Neptune and Saturn in size. By November he and his colleagues were certain the find was worth publishing, even if it proved not to be a world at all. (It would not be the first time our neighboring star system has fooled astronomers. Peer-reviewed claims of a small planet around Alpha Centauri B in 2012 evaporated a few years later, found to be products of stellar noise.)

"In a way, I hope that we haven't detected anything this time, too," Wagner says. "Because what I'm most excited to find is an Earth-like planet in the habitable zone. The presence of a Neptune in the habitable zone of Alpha Centauri A would not rule out something smaller nearby, but it would limit some of the area in which we

could hope for rocky worlds to exist there in the first place."

There is no shortage of other possible explanations for the weak signal, which is essentially a thermal wisp of infrared photons—that is, of heat—that seems to originate from a source at the outer edge of Alpha Centauri A's habitable zone. In visible light, a sunlike star outshines a small, rocky planet by a factor of billions. But in infrared, the star is dimmer and the planet is at its brightest, so this contrast ratio is "only" measured in millions. For decades the difficulty of achieving even this more modest measurement limited direct imaging to hot giant planets orbiting far from their stars. That is, until NEAR was built. It is a midinfrared coronagraph, a specialized instrument designed to blot out the bulk of a star's thermal glow at a tight wavelength of 10 microns. Augmented by adaptive optics to compensate for the blurring turbulence of Earth's atmosphere, in operation it switches its focus between Alpha Centauri A and B every tenth of a second, using observations of each star to help calibrate those of the other. It progressively winnows out starlight and stacks frame after frame to allow any faint planetary light to accumulate and eventually be seen. But rather than betraying the presence of a planet, any resulting blip could instead be a far-distant background object, a clump of starlight-warmed dust or an asteroid belt circling around a star, or even the errant play of stray photons leaking from beamlines and spraying across sensitive optics inside the instrument. Wagner and his co-authors have already ruled out the first possibility (no known background star or galaxy can account for the blip), but the others remain in play to various degrees.

Confirmation of the blip's planetary status should have been relatively straightforward: simply attempt to observe it again after sufficient time has passed; if it is in fact a planet, its orbital motion will have swept it to a new and very different position around its star. Subsequent, more time-intensive studies with NEAR could then crudely measure the blip's colors to help eliminate the "dust cloud" hypothesis. But this was not to be—not yet, anyway—as the ensuing COVID pandemic shut down astronomical observatories and most everything else around the globe. Wagner says the team has applied for additional time to use NEAR on the VLT, but the proposal has yet to be approved.

"The timing is such a shame," says Debra Fischer, a veteran planet hunter at Yale University. She is unaffiliated with the study, but her work with her student Lily Zhao has placed the best-yet constraints on the planets that may or may not exist in the Alpha Centauri system. "If it's in the habitable zone around Alpha Centauri A, that's an Earth-like orbit, so observing six months later would probably have nailed it," Fischer says. "Without that, this isn't a planet-detection paper; it's a demonstration of NEAR's capability to monitor Alpha Centauri in the midinfrared. But if this turns out to be right—oh, my God, it's huge."

BRAVE NEW WORLDS

For now NEAR is the only coronagraph on Earth with a realistic chance of imaging Alpha Centauri's hidden worlds. But other instruments and facilities are already waiting in the wings to apply their own scrutiny to the system. Fischer's high-precision EXPRES radial velocity spectrograph and an even more advanced European counterpart, ESPRESSO, are both already operational. They could help indirectly confirm the planet candidate and others and could estimate their masses by watching for periodic wobbles each world's orbital tugging induces on its host star. A related technique, astrometry, could do much the same thing, pinpointing planetary masses by measuring how each world's gravitational influence slightly shifts its star's position in the plane of the sky. Such observations using the Atacama Large Millimeter Array in Chile or even a modest, Breakthrough-funded dedicated space mission could occur later this decade.

NASA's James Webb Space Telescope, slated to launch in late October, would also be capable of directly imaging the candidate planet given one full day of observing time, according to a recent study led by one of Webb's foremost scientists, Charles Beichman of the California Institute of Technology. "Because Alpha Centauri A is a twin of our own sun and less than five light-years away, it really is our closest solar neighbor," Beichman says. "That makes it first among equals of all the stars in the sky. No other

system will lend itself to more detailed possible studies over the next several decades."

The space agency's follow-up mission to Webb, the Nancy Grace Roman Space Telescope, will also carry a coronagraph as a technology demonstration that could (with certain tweaks now being actively considered) potentially snap pictures of the candidate.

And, around the same time Roman may launch, a new generation of sophisticated coronagraphs mated to gargantuan ground-based observatories should begin operations that could in mere minutes produce images of Centauri planets that would currently require hours on hours of NEAR's time on the VLT. Armed with starlight-gathering mirrors 30 meters or more across, ESO's European Extremely Large Telescope and its American counterpart, the Giant Magellan Telescope, could both in theory gather enough light from a habitable-zone Neptune around Alpha Centauri A to study its atmosphere, sniffing out what familiar or alien chemistry occurs there. (A third behemoth, the U.S.'s Thirty Meter Telescope, is currently planned for a site in the Northern Hemisphere from which Alpha Centauri would not be visible.) Finally, NASA and other space agencies are now studying concepts for multibillion-dollar space telescopes for the 2030s and beyond. Some of these could image and search for signs of life on small rocky planets around Alpha Centauri as well as many other nearby stars.

All of which means that, even if this latest candidate from Alpha Centauri proves spurious, it still signals something quite real: a looming sea change, in which planet-hunting astronomers shift from safe, statistical surveys to the more daring in-depth study of individual worlds, some of which might harbor life.

"Whether this thing is real is, to me, almost secondary," says study co-author Olivier Guyon, an innovator in direct imaging and chair of Breakthrough Watch. "Because either way, it shows we're clearly opening a new era in the history of astronomy where, finally, after more than 20 years of hard work, we can at last perform direct imaging of another star's habitable zone. This is the 'game on' moment for the field."

—Lee Billings

Mystery of Spinning Atomic Fragments Solved at Last

New experiments have answered the decades-old question of how pieces of splitting nuclei get their spins

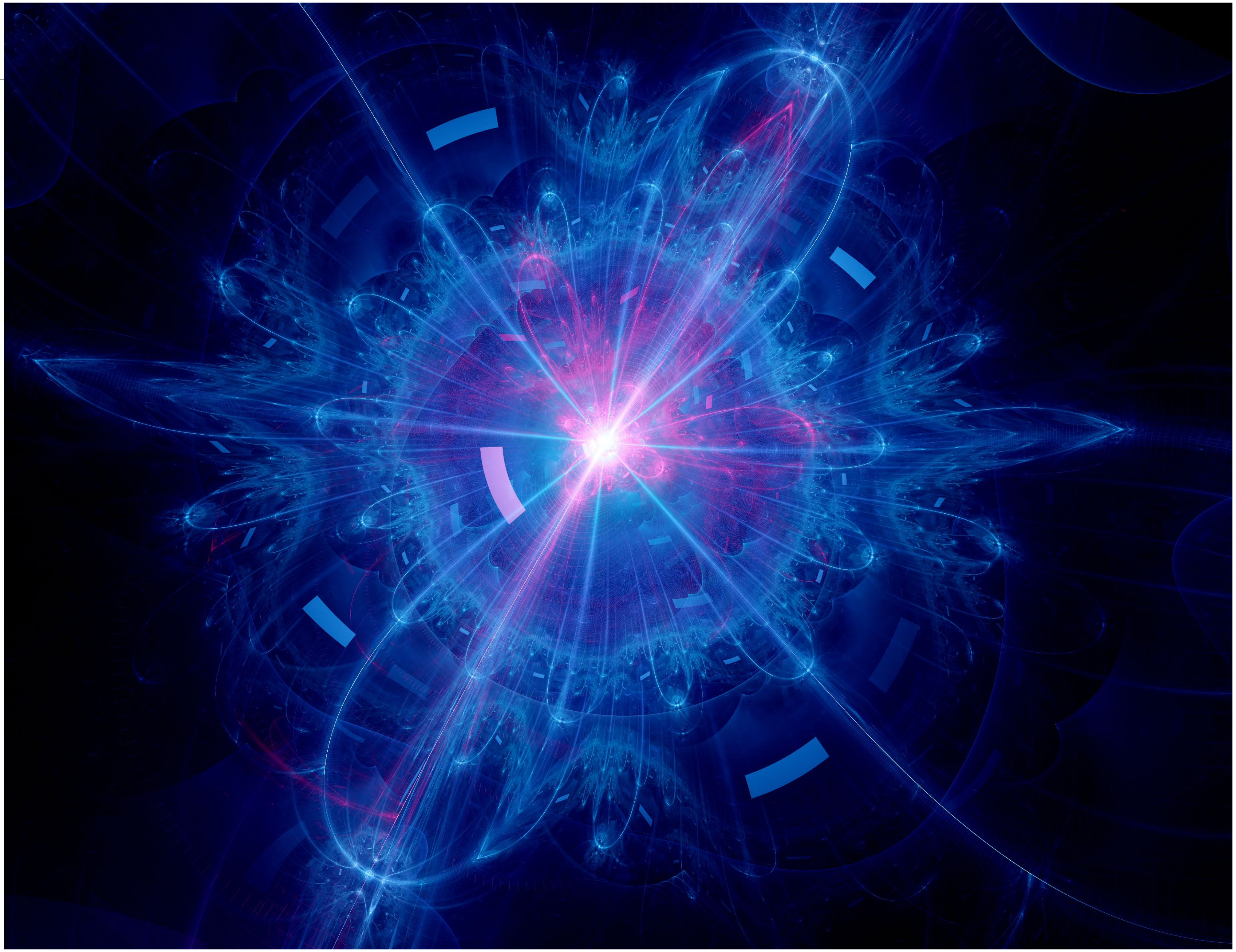
For over 40 years, a subatomic mystery has puzzled scientists: Why do the fragments of splitting atomic nuclei emerge spinning from the wreckage? Now researchers find these perplexing gyrations might be explained by an effect akin to what happens when you snap a rubber band.

To get an idea why this whirling is baffling, imagine you have a tall stack of coins. It would be unsurprising if this unstable tower fell. But after this stack collapsed, you likely would not expect all the coins to begin spinning as they hit the floor.

Much like a tall stack of coins, atomic nuclei rich in protons and neutrons are unstable. Instead of collapsing, such heavy nuclei are prone to splitting, a reaction known as nuclear fission. The resulting shards come out spinning, which can prove especially bewildering when the nuclei that split were not spinning themselves. Just as you would not expect an object to start moving on its own without some force acting on it, a body beginning to spin in absence of an initiating torque would seem decidedly supernatural, in apparent violation of the law of conservation of angular momentum.

This "makes it look like something was created from nothing," says study lead author Jonathan Wilson, a nuclear physicist at Université Paris-Saclay's Irene Joliot-Curie Laboratory in Orsay, France. "Nature pulls a conjuring trick on us. We start with an object with no spin, and after splitting apart, both chunks are spinning. But, of course, angular momentum must still be conserved."

Previous research found that fission begins when the shape of a nucleus becomes unstable as a consequence of jostling between the protons; because they are positively charged, they naturally repel each other. As the nucleus elongates, the nascent fragments form a neck between them. When the nucleus ultimately disintegrates, these pieces move apart rapidly, and the neck snaps quickly, a process known as scission.



Over the decades scientists have devised a dozen or so different theories for this spinning, Wilson says. One class of explanations suggests the spin arises before scission given the bending, wriggling, tilting and twisting of the particles making up the nucleus before the split, motions resulting from thermal excitations or quantum fluctuations, or both. Another set of ideas posits that the spin occurs after scission consequent to forces such as repulsion between the protons in the fragments. Yet "the results of the experiments looking into this all contradicted each other," Wilson says.

Now Wilson and his colleagues have conclusively determined that this spinning results after the split, findings they detailed online February 24 in *Nature.* "This is wonderful new data," says nuclear physicist George Bertsch of the University of Washington, who did not participate in this study. "It's really an important advance in our understanding of nuclear fission."

In the new study, the scientists examined nuclei resulting from the fission of various unstable elemental isotopes: thorium 232, uranium 238 and californium 252. They focused on the gamma rays released after nuclear fission, which encoded information on the spin of the resulting fragments.

If the spinning resulted from effects before scission, one would expect the fragments to have equal and opposite spins. But "this is not what we observe," Wilson says. Instead it appears that each fragment spins in a manner independent of its partner, a result that held true across all examined batches of nuclei regardless of the respective isotopes.

The researchers suspect that when a nucleus lengthens and splits, its remnants start off somewhat resembling teardrops. These fragments

each possess a quality akin to surface tension that drives them to reduce their surface area by adopting more stable spherical shapes, much as bubbles do, Wilson explains. The release of this energy causes the remnants to heat and spin, a bit like how stretching a rubber band to the point of snapping leads to a chaotic, elastic flailing of fragments.

Wilson adds this scenario is complicated by the fact that each chunk of nuclear debris is not simply a uniform piece of rubber but rather resembles a bag of buzzing bees, given how its particles are all moving and often colliding with one another. "They're like two miniature swarms that part ways and start doing their own things," he says.

All in all, "these findings give big support to the idea that the shapes of nuclei at the point at which they're coming apart is what determines their energy and the properties of the fragments," Bertsch says. "This is important for directing the theory of fission to be more predictive and allows us to more confidently discuss how it can make elements."

One reason Wilson suggests previous analyses of fissioning atoms did not deduce the origins of these gyrations was because they did not have the benefit of modern, ultra-high-resolution detectors and contemporary, computationally intensive data-analysis methods. Previous work also often focused more on exploring the exotic structures of "extreme" superheavy neutron-rich nuclei to see how standard nuclear theory could account for such distinctly unusual cases. Much of that prior work deliberately avoided collecting and analyzing the huge amount of extra data needed to investigate how the nuclear fragments spun, whereas this new study explicitly focused on analyzing such details, he explains. "For me, the most surprising thing about the measurement is that it could be done at all with such clear results," Bertsch says.

Wilson cautions more work is needed to explain how exactly spin results after scission. "Our theory is simplistic, for sure," he notes. "It can explain about 85 percent of the variations we see in spin as a function of mass, but a more sophisticated theory could be able to make more accurate predictions. It's a starting point; we're not claiming anything more." Other scientists at the European Commission's Joint Research Center facility in Geel, Belgium, he adds, have now also confirmed the observations with a different technique. Those independent results should be published soon.

"Even though fission was discovered 80 years ago, it's so complex that we're still seeing interesting results today."
—Jonathan Wilson

These findings may not only solve a decades-long mystery but could help scientists design better nuclear reactors in the future. Specifically, they could help shed light on the nature of the gamma rays emitted by spinning nuclear fragments during fission, which can heat reactor cores and surrounding materials. Currently these heating effects are not fully understood, particularly how they vary between different types of nuclear-power systems.

"There's up to a 30 percent discrepancy between the models and the actual data about these heating effects," Wilson says. "Our findings are just a part of the full picture one would want in simulating future reactors, but a full picture is necessary."

These studies of subatomic angular momentum could also help scientists figure out which superheavy elements and other exotic atomic nuclei they can synthesize to shed more light on the still murky depths of nuclear structure. "About 7,000 nuclei can theoretically exist, but only 4,000 of those can be accessed in the laboratory," Wilson says. "Understanding more about how spin gets generated in fission fragments can help us understand what nuclear states we can access."

Future research, for instance, could explore what might happen when nuclei are driven to fission when bombarded by light or charged particles. In such cases, Wilson says, the incoming energy could lead to prescission influences on the spinning of the resulting fragments.

"Even though fission was discovered 80 years ago, it's so complex that we're still seeing interesting results today," Wilson says. "The story of fission is not complete—there are more experiments to do, for sure."

—Charles Q. Choi

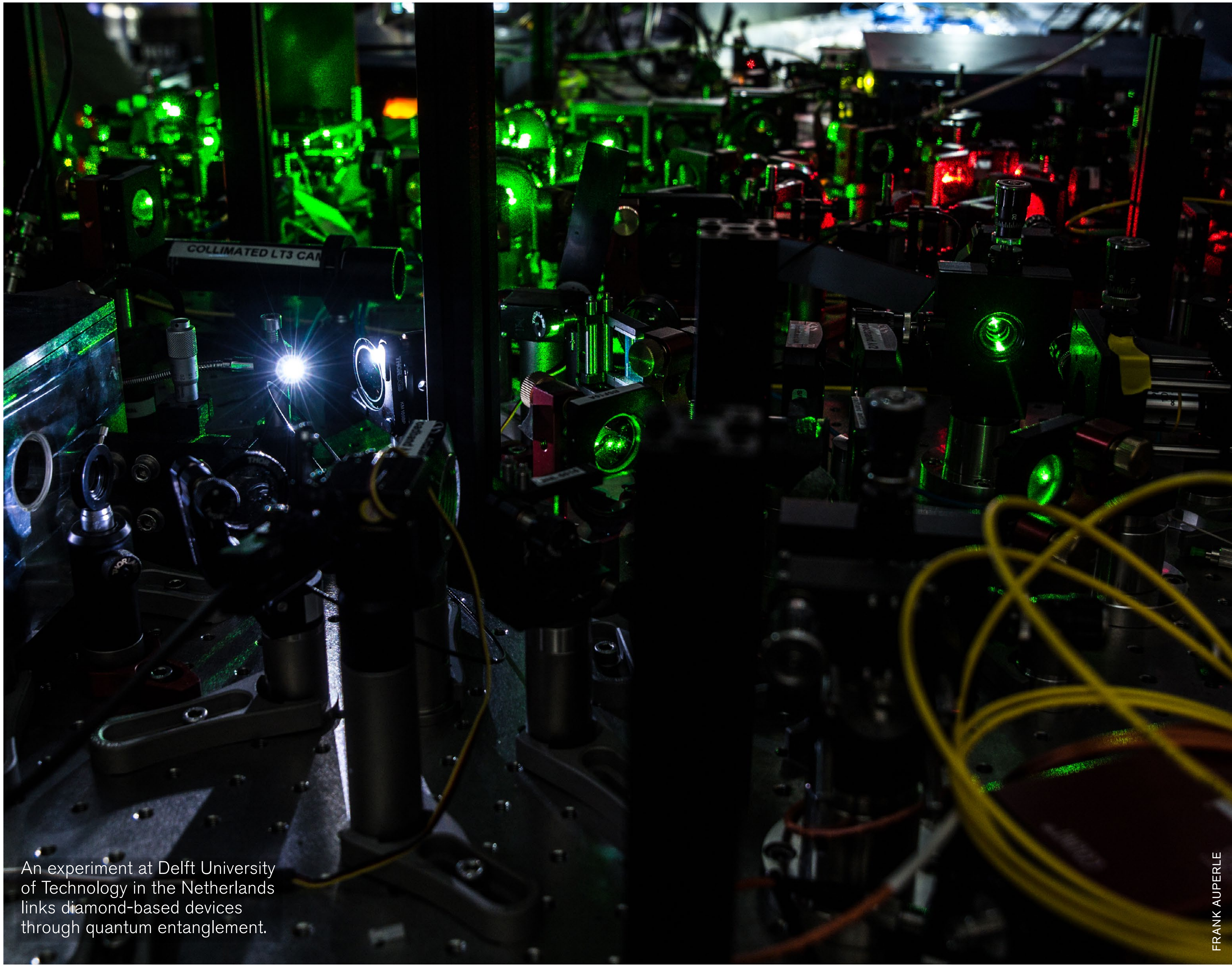
Quantum Network Is Step toward Ultrasecure Internet

Experiment connects three devices with entangled photons, demonstrating a key technique that could enable a future quantum Internet

Physicists have taken a major step toward a future quantum version of the Internet by linking three quantum devices in a network. A quantum Internet would enable ultrasecure communications and unlock scientific applications such as new types of sensor for gravitational waves and telescopes with unprecedented resolution. The results were reported on February 8 on the arXiv preprint repository.

"It's a big step forward," says Rodney Van Meter, a quantum-network engineer at Keio University in Tokyo. Although the network doesn't yet have the performance needed for practical applications, Van Meter adds, it demonstrates a key technique that will enable a quantum Internet to connect nodes over long distances.

Quantum communications exploit



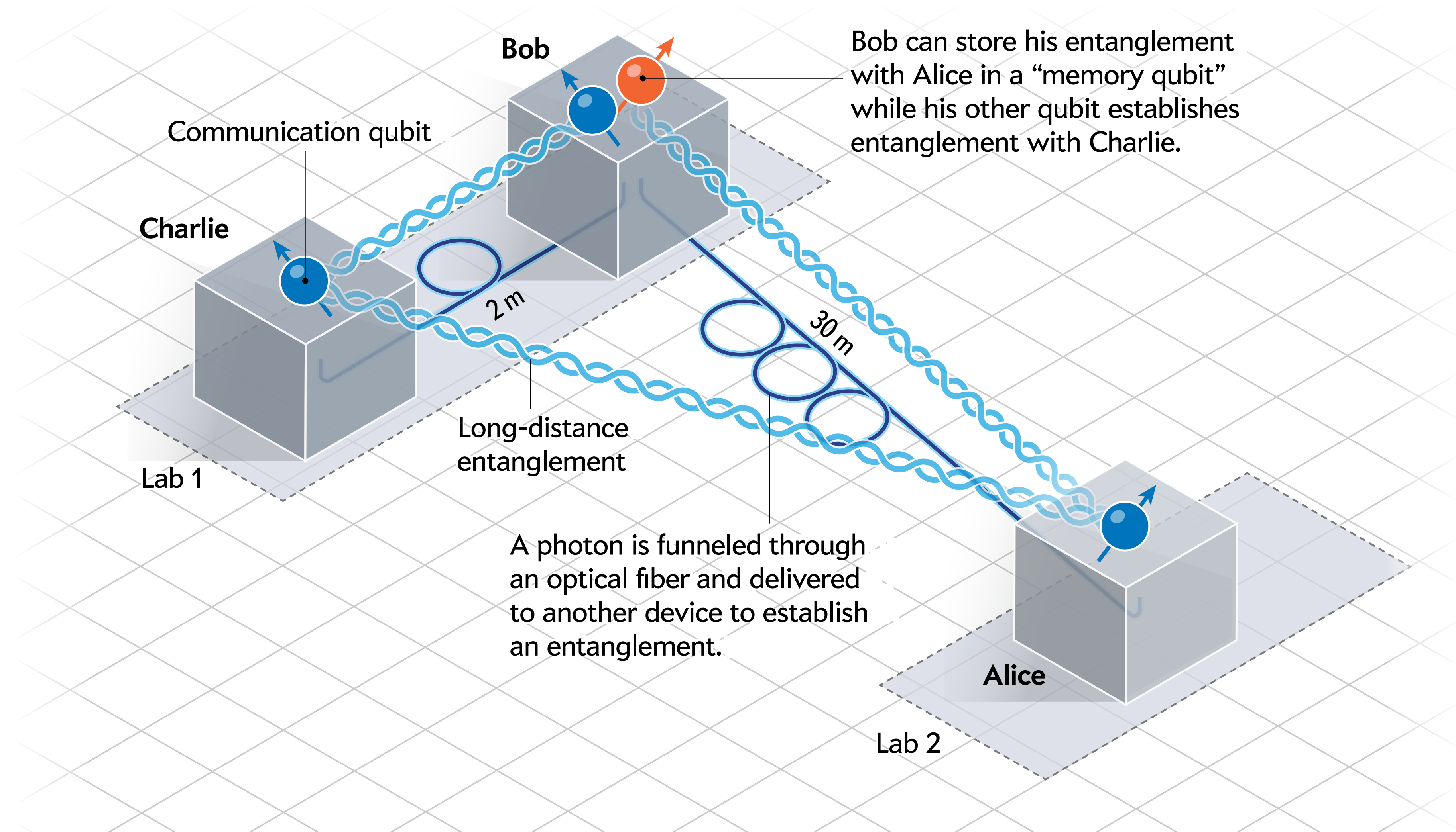
An experiment at Delft University of Technology in the Netherlands links diamond-based devices through quantum entanglement.

FRANK AUPERLE

phenomena that are unique to the quantum realm—such as the ability of elementary particles or atoms to exist in a superposition of multiple simultaneous states or to share an entangled state with other particles. Researchers had demonstrated the principles of a three-node quantum network before, but the latest approach could more readily lead to practical applications.

Quantum Network

Physicists have created a network that links three quantum devices using the phenomenon of entanglement. Each device holds one qubit of quantum information and can be entangled with the other two. Such a network could be the basis of a future quantum internet.



ENTANGLED WEB

At the heart of quantum communications is information stored in qubits—the quantum equivalent of the bits in ordinary computers—which can be programmed to be in a superposition of a 0 and a 1. The main purpose of a quantum network is to enable qubits on a user's device to be entangled with those on someone else's. That entanglement has many potential uses, starting with encryption: because measurements on entangled objects are always correlated, by repeatedly reading the states of their qubits, the users can generate a secret code that only they know.

In the latest demonstration, physicist Ronald Hanson of the Delft University of Technology in the Netherlands and his collaborators linked three devices in such a way that any two devices in the network ended up with mutually entangled qubits. They also put qubits at all three devices in a three-way entangled state, which, among other applications, can enable three users to share secret information.

Each of the Delft devices stores quantum information in a synthetic diamond crystal—more precisely, in the quantum states of a defect in the crystal, where a nitrogen atom replaces one of the carbons.

In such a diamond device, researchers can prod the nitrogen qubit to emit a photon, which will be automatically entangled to the atom's state. They can then funnel the photon into an optical fiber and deliver it to another device, helping to establish entanglement between remote qubits. In a tour-de-force experiment in 2015, the Delft team successfully entangled two diamond-based devices and used them to confirm some crucial predictions of quantum mechanics.

QUANTUM MEMORY

One of the three devices in the team's latest experiment—the one in the middle of the network—was also set up to store information in a "quantum memory," which can hold data for longer than the other qubits and was key to setting up the three-way entanglement. The memory qubit used carbon 13, a nonradioactive isotope that makes up around 1 percent of naturally occurring carbon. Carbon 13 has an extra neutron in its nucleus, so it acts like a bar magnet. The researchers used an active electron in the nitrogen defect as a sensor to locate a nearby carbon 13 nucleus. By manipulating the electron, they were able to nudge the carbon nucleus into specific quantum states, turning it into an additional qubit. Such carbon quantum memories can keep their quantum states for one minute or more—which in the subatomic world is an eternity.

The carbon memory enabled the researchers to set up their three-device network in stages. First, they entangled one of the end nodes with the nitrogen in the central node. Then they stored the nitrogen's quantum state in a carbon memory. This freed the central nitrogen qubit to become entangled with the qubit at the third node. As a result, the central device had one qubit entangled with the first node and another simultaneously entangled with the third.

The technique required years of refinement. The carbon qubit needs to be sufficiently well insulated from its environment for its quantum state to survive while the physicists conduct further operations—but still be accessible so that it can be programmed. "You want to store a quantum state, so it should be shielded. But it should not be shielded too much," Hanson told a reporter during a visit to his lab in 2018.

This and other challenges made the experiment more difficult than a two-node network, says Tracy Northup, a physicist at the University of Innsbruck in Austria. "Once you seriously try to link three, it gets significantly more complicated."

Storing information in a node enabled the team to demonstrate a technique called entanglement swapping, which could turn out to be as crucial for a future quantum Internet as routers are for the current one.

MATERIAL CONCERNS

The Delft team is not the first to have successfully linked three quantum memories: in 2019 a team led by physicist Pan Jianwei of the University of Science and Technology of China in Hefei did so using a different type of qubit, based on clouds of atoms rather than individual atoms in a solid object. But that experiment could not yet produce entanglement on demand, Northup says. By detecting photons, the Hefei team could only "retroactively extract the fact that the entanglement was there," not that it is still available for further use.

Van Meter says that atomic-cloud qubits are more limited in what they can do, so it could be very difficult for the Hefei team to do entanglement swapping—although perhaps not impossible. "I would never say never with the Pan group."

Mikhail Lukin, a physicist at Harvard University, calls the Delft experiment "heroic" but adds that its performance is slow, showing that nitrogen defects also have limitations. Lukin's team is working on similar experiments in diamond with silicon defects, which are much more efficient at interacting with photons, he says. Other teams have built networks with ions trapped in an electromagnetic field or with defects in crystals of rare-earth elements, which can interact with infrared photons that can travel along kilometers of optical fiber without significant losses. (Optical fibers are poor at carrying the visible-light photons emitted by nitrogen defects in diamond.)

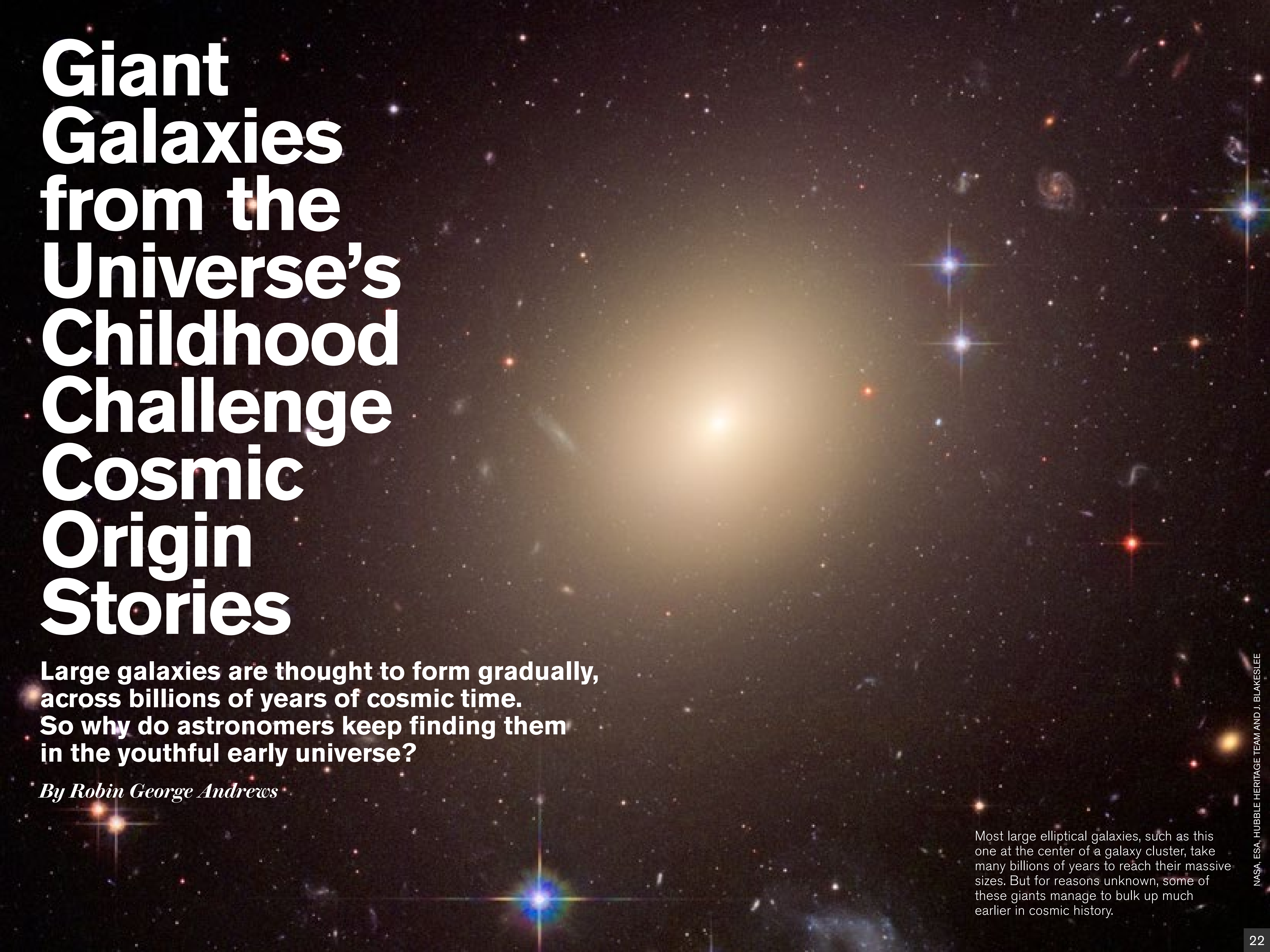
In their paper, Hanson and his co-authors suggest that their techniques will "provide guidance for similar platforms reaching the same level of maturity in the future."

—Davide Castelvecchi

Giant Galaxies from the Universe's Childhood Challenge Cosmic Origin Stories

Large galaxies are thought to form gradually, across billions of years of cosmic time. So why do astronomers keep finding them in the youthful early universe?

By Robin George Andrews



Most large elliptical galaxies, such as this one at the center of a galaxy cluster, take many billions of years to reach their massive sizes. But for reasons unknown, some of these giants manage to bulk up much earlier in cosmic history.

NASA, ESA, HUBBLE HERITAGE TEAM AND J. BLAKESLEE

Robin George Andrews is a volcanologist and science writer based in London.

RECENTLY AN INTERNATIONAL TEAM OF ASTRONOMERS TRAVELED BACK in time to when our universe was just 1.8 billion years old. They did not go directly, of course, but settled for the next best thing: gathering 17 hours' worth of starlight from a single small patch of the distant cosmos with the Large Binocular Telescope Observatory atop Mount Graham in southeastern Arizona. Such clock-rewinding virtual voyages are routine in astronomy—light's finite speed ensures that the deeper into space you see, the further back in time you gaze. And many observatories around the globe can gather faint photons from ancient skies. But this particular cosmic jaunt concerned something special—even disturbing: an abnormally hefty elliptical galaxy dubbed C1-23152. This egg-shaped aggregation of stars is so outsize that it defies conventional models of its origins. Simply put, C1-23152 seems to be too big to fit the early universe.

It is thought that the first galaxies were relatively minuscule, clumping together from smaller building blocks bit by bit and only reaching gargantuan sizes after billions of years of growth. Boasting an estimated 200 billion solar-mass stars, C1-23152 tips and then overturns the scales for this scenario. And it is not alone. Over the past decade astronomers have discovered several very ancient, very big galactic behemoths. In 2017, for example, a pair of extremely large galaxies—one capable of churning out 2,900 solar masses of stars per year—were found to exist less than 800 million years after the big bang. In 2019 a family of 39 huge galaxies—each a star factory manufacturing perhaps 200 solar-mass stars per year—were found zipping through the universe within two billion years of its birth.

Does this ever increasing number of venerable vast objects threaten to bring down the traditional model of galaxy formation? "The trick here is: How many do you have?" says Marcel Neeleman, an astronomer at the Max Planck Institute for Astronomy in Heidelberg, Germany, who was not involved with the new study. A handful will not matter; the universe is big enough that odd things will crop up every now and then. But if future, increasingly advanced telescopes manage to find far more of them, then perhaps these colossal galaxies from the universe's childhood may break our understanding of the cosmos.

A LONG TIME AGO IN A GALAXY FAR, FAR AWAY

What has become the widely accepted model of galaxy formation is largely gleaned from simulations of cosmic evolution that reproduce our observations of the local universe—the stuff we can see near the Milky Way.

After the big bang, the cosmos expanded and stretched out fairly evenly in all directions. But, Neeleman says, you get "tiny density variations in the fabric of the universe." These variations are home to clumps of dark matter, a substance that emits little, if any, electromagnetic radiation. As such, dark matter has yet to be directly detected, but observations of galaxies indicate that this invisible mass produces its own gravitational pull. That means that these dark matter clumps attract "ordinary" matter (the stuff we humans can detect and interact with), most of which is gas. The gas tumbles into these gravity wells and squashes together to trigger star formation. More matter continues to tumble into these ever expanding wells—called dark matter "halos" by astronomers—gradually forming bigger and bigger structures over the 13.8-billion-year lifetime of the universe. This process should more or less create the distribution of galaxies we see today, says Paolo Saracco, an astronomer at Italy's National Institute for Astrophysics and the lead author of a study reporting the recent observations of C1-23152.

That is why ancient massive galaxies are problematic. "For our current understanding of galaxy formation, we sort of built on the galaxies we knew at the time," says Coral Wheeler, an astronomer at California State Poly-

technic University, Pomona, who was not involved with the new study. These galaxies did not include the very old, small or big ones. Looking further back in time with increasingly powerful telescopes began to reveal these apparent outliers. And as the tally of anomalous entities rose, astronomers started wondering if their models needed to expand to make room for them or if those models would buckle and break under the strain.

"When you run a simulation, there's a trade-off between how big of a volume you want to simulate and how much detail you can simulate because of the computer power you have or don't have."

—Ben Forrest

As reported in the *Astrophysical Journal* in December 2020, Saracco's team managed to extract some juicy details out of C1-23152. Light from far-distant cosmic regions is stretched by the expanding universe as it travels to Earth. The more it is stretched, the greater its shift toward the longer-wavelength "redder" section of the electromagnetic spectrum. This "redshift" of C1-23152's starlight indicates that it appeared 12 billion years ago, way back in the universe's youth. The fact that this galaxy is both ancient and massive alone is problematic enough for traditional slowly-but-surely models of galaxy formation. But it did not just appear fully formed. Saracco and his team's real breakthrough was to trace C1-23152's history of star formation from across the universe.

The key to that breakthrough was seeing the giant galaxy's spectrum—a rainbowlike measurement of the various wavelengths, or colors, that an object emits or absorbs. Particular color combinations distinguish specific elements, which means this spectral symphony can be used to determine the composition of a galaxy's stars. Using that power, Saracco says, "for the first time, we derived, with very good accuracy, the mean age of the stellar population inside [C1-23152] and the time necessary to form those stars."

The number of elements in C1-23152 that were found to be heavier than hydrogen and helium—which astronomers collectively refer to as "metals"—hinted at its strangeness. Metals are produced by star formation, which jettisons them into a galaxy's interstellar medium through supernovae—making them available for next-generation stars to use. More metals equal more cycles of star formation, and it took present-day massive galaxies many billions of years to become metal-rich. C1-23152's spectrum revealed the galaxy to be a veritable metal bonanza back in its early days, which means it made a lot of stars very rapidly not long after it first formed.

How rapidly? The spectral features of stars can answer that question, too, because they reveal which ones have elements typical of younger or older stars. The youngest stars in C1-23152 are roughly 150 million years old. The most ancient are about 600 million years old. That means the galaxy made some 200 billion solar masses in just half a billion years—a rate of 450 stars per year, more than one per day. The figure is almost 300 times greater than estimates of the Milky Way's current output. If most galaxies are slow-burning log fires, with new flames popping up every so often, C1-23152 is a gasoline-soaked bonfire.

C1-23152 and its similar cousins present astronomers with a potentially model-breaking conundrum: How can massive galaxies be assembled and set alight so quickly so early on? For now the answer, in short, is that they can't.

GROWING THE UNIVERSE IN A BOX

For some time, simulations have struggled to grow these ginormous galaxies. But that does not mean they simply cannot do so. Instead the trouble may lie in how they are programmed.

"When you run a simulation, there's a trade-off between how big of a volume you want to simulate and how much detail you can simulate because of the computer power you have or don't have," says Ben Forrest, an astronomer at the University of California, Riverside, and a co-author of the new study. If these ancient massive galaxies are rare, perhaps we are not using big enough boxes to give one the chance to pop up. "Maybe some of the simulations aren't really covering enough volume," he says.

Quickly tweaking them to spawn mega galaxies from the early eras of cosmic time is not easy either. "It takes a long time to rerun them. If you want to change something, you've got to be pretty sure that's right and that's what you want to do," Forrest says.

Some of the latest iterations of simulations, with better data and computing power, do predict these massive galaxies to exist in small numbers at early times, he adds. But unlike what is being observed in reality, they tend to still be making stars. Ancient galaxies, including C1-23152, abruptly shut off star formation after a productive peak—either because they run out of hydrogen and helium fuel or because the radiation shooting out from fresh crops of stars and other overzealous astrophysical sources cooks that gas and blasts it out of reach. Clearly, some ingredients are still missing from our virtual recipes, so we cannot rely on them for an explanation yet.

Scientists have found clues elsewhere that may account for these ancient mega galaxies. Anastasia Fialkov, a cosmologist at the University of Cambridge, who was

not involved with the latest work, says that, unlike full-blown simulations, analytic physics calculations can "take into account the whole volume of the universe." And they suggest that a small number of dark matter halos capable of initiating star formation show up just 40 million years after the big bang.

That time is significantly earlier than the majority of dark matter halos that turn up later on in the youthful epochs of the universe—those thought to be responsible for seeding much of the galaxies we see today. Instead the halos that appeared 40 million years after the big bang would have been capable of seeding the beginnings of the ancient massive galaxies that would eventually become detectable via our telescopes. The early universe was also denser, Wheeler notes. That would make scooping up star-making hydrogen and helium around these primordial dark matter halos, and eventually galaxies, fairly effortless.

Another option, Neeleman says, is that a combination of things could have occurred. Rare hyperdense pockets of the universe would permit multigalaxy mergers very early on, while streams funneling gas into the hearts of galaxies could supercharge star formation.

In any event, the emergence of huge ancient galaxies is more easily explained if dark matter is cold. Here "cold" means the dark matter moves relatively slowly. "Hot" dark matter would move at velocities approaching the speed of light. Generally speaking, the colder the dark matter, the easier it can condense into galaxy-seeding halos. This assumption may not necessarily be correct, but "cold dark matter is the simplest dark matter scenario that works," Fialkov says.

It is unclear which amalgam of these events, if any, best explains C1-23152's origins and evolution, let alone its colossal cousins. "This is not a special corner of the universe" we are looking at, Saracco says. More important, nothing here threatens to overthrow the traditional slowly-but-surely model of galaxy formation, he says.

"There's so much uncertainty that goes into galaxy formation."
—Coral Wheeler

These ancient, massive galaxies just represent another pathway for galaxies to take.

BACK TO THE FUTURE

The traditional model survives for now but only, in part, because few of these massive galaxies have been found. "We're dealing with small-number statistics," Forrest says. Scientists do not have a good grasp of the true amount of the behemoths, however. Until that changes, understanding what impact they have on our cosmic comprehension and how galaxies evolve in different ways will remain ambiguous.

Perhaps we have already seen many more of these old megagalaxies than we yet realize. For detailed studies, our telescopes are often drawn to the brightest massive but burnt-out galaxies before their nature is revealed. Astronomers have spotted fainter objects with otherwise similar characteristics hanging about in the early universe, however, says Stijn Wuyts, an astronomer at the University of Bath in England, who was not involved with the recent work. They could turn out to be merely less massive galaxies or yet more ancient massive ones observed long after their star-forming prime. Are these objects dimmer candles closer to home or vast pyres farther afield?

As ever, more data are required. And several upcoming telescopes will aid us in this time-traveling galactic census.

First, suspicious bright splotches in the distant past need to be spotted. "If you want to get a bunch of candidates, then a wide field of view is great," Forrest says. The Nancy Grace Roman Space Telescope, formerly known as WFIRST and currently targeted for a 2025 launch, will have a field of view equivalent to 100 Hubble Space Telescopes: its wide, sensitive eyes will see plenty of possible ancient massive galaxies.

Those candidates will then need to be forensically examined by looking at their various spectra to determine their properties and confirm they are indeed such galaxies and not imposters. "Ideally, you want a really big telescope," Forrest says. "That gives you more collecting area—it's a bigger bucket for photons to go into from an object." Hawaii's Thirty Meter Telescope could be suitable if it is built, and the Extremely Large Telescope could fit the bill as well. The James Webb Space Telescope—which is finally launching this October after an abundance of delays—should work well, too. "It's not as big," Forrest says. "The bucket for the photons is a little bit smaller, but then you don't have to look through the atmosphere," so there is less interference to deal with.

Saracco is particularly excited for these upcoming next-generation magnifying glasses because they will do more than merely finding extremely distant objects. "We will be able to observe inside [a] galaxy, at single star-forming regions," he says. In other words, instead of a blurry picture of a galaxy's bulk characteristics, astronomers will get a more granular view—the difference between a rough sketch and a detailed painting—opening up a new chapter in our understanding of how galaxies form.

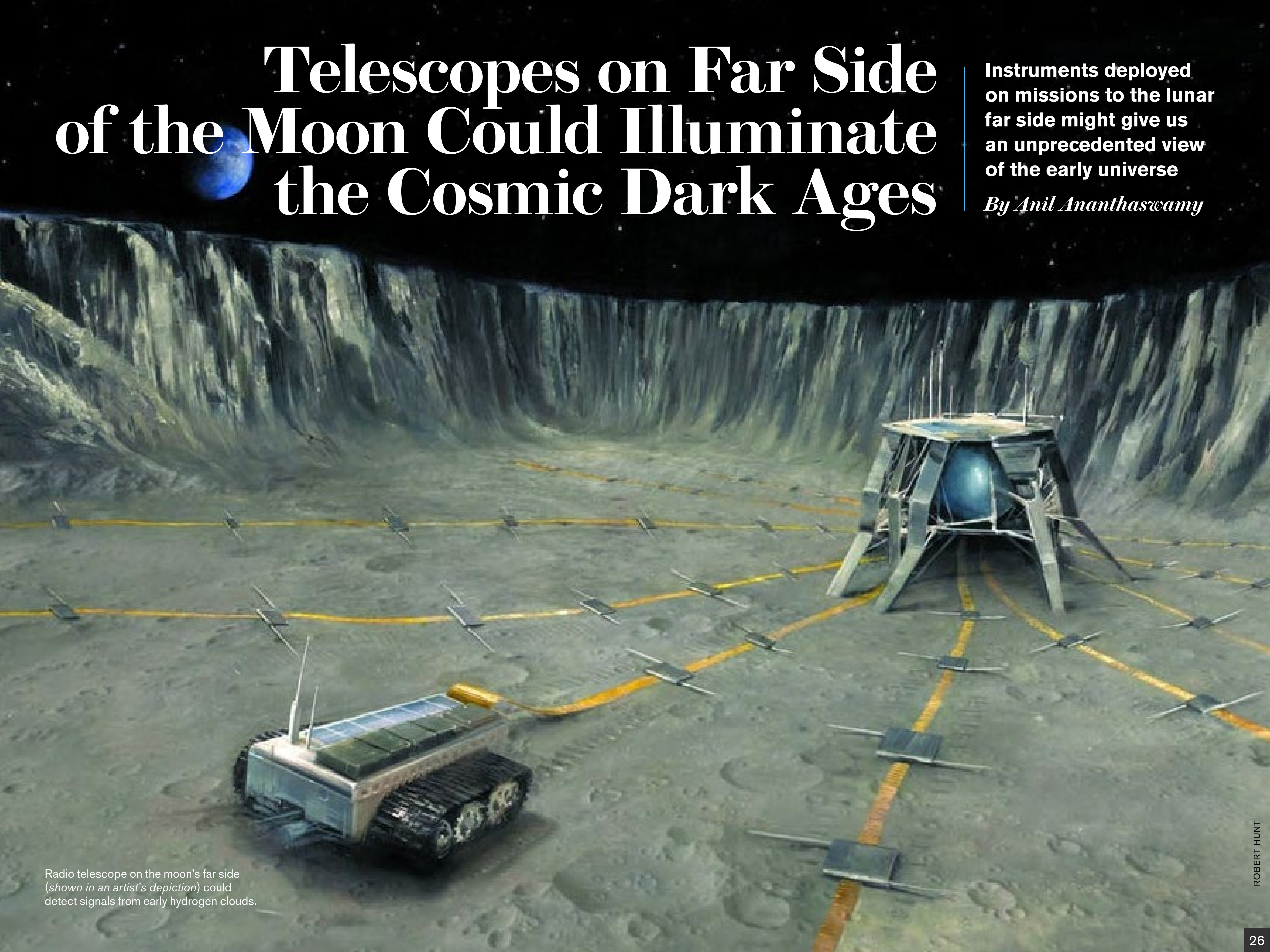
Until this help arrives, this scientific field will remain in its infancy. "There's so much uncertainty that goes into galaxy formation," Wheeler says.

It can be unnerving to chase monsters in the dark. They threaten the dogmas of the era, forcing us to expand our earlier models to fit them. And if those models stretch to the point of breaking, that's okay. "We want to challenge, in some way, the model," Wheeler says. "When things don't match, that's when it gets interesting." SA

Telescopes on Far Side of the Moon Could Illuminate the Cosmic Dark Ages

Instruments deployed on missions to the lunar far side might give us an unprecedented view of the early universe

By Anil Ananthaswamy



Radio telescope on the moon's far side (*shown in an artist's depiction*) could detect signals from early hydrogen clouds.

ROBERT HUNT

Anil Ananthaswamy is author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

THE FAR SIDE OF THE MOON IS A STRANGE and wild region, quite different from the familiar and mostly smooth face we see nightly from our planet. In 1959 the Soviet Luna 3 space probe took the first photographs of this hidden region. Instead of wide plains, the images showed a moonscape spiked with mountains. Observations since then have shown that the far side is also full of rugged craters, and within them there are yet more craters. Soon this rough terrain and the space just above it will have even stranger features: it will be teeming with radio telescopes, deployed by a new generation of robotic rovers and lunar orbiters.

Astronomers are planning to make the moon's distant side our newest and best window on the cosmic dark ages, a mysterious era hiding early imprints of stars and galaxies. Our universe was not always filled with these bright objects that shine across today's skies. About 380,000 years after the big bang, the universe cooled, and the first atoms of hydrogen formed. Gigantic clouds of this element soon filled the cosmos. But for a few hundred million years, everything remained dark, devoid of stars. Then came the cosmic dawn: the first stars flickered, galaxies swirled into existence and slowly the universe's large-scale structure took shape.

The seeds of this structure must have been present in the dark-age hydrogen clouds, but the era has been impossible to probe using optical telescopes—there was no light. And although this hydrogen produced long-wavelength (or low-frequency) radio emissions, radio telescopes on Earth have found it nearly impossible to detect them. Our atmosphere either blocks or disturbs these faint signals; those that get through are swamped by humanity's radio noise.

Scientists have dreamed for decades of studying the cosmic dark ages from the moon's far side, shielded from earthly transmissions and untroubled by any significant atmosphere to impede cosmic views. Now multiple space agencies plan lunar missions carrying radio-wave-detecting instruments—some within the next three years—and astronomers' dreams are set to become reality.

"If I were to design an ideal place to do low-frequency radio astronomy, I would have to build the moon," says astrophysicist Jack Burns of the University of Colorado Boulder. "We are just now finally getting to the place where we're actually going to be putting these telescopes down on the moon in the next few years."

THE HYDROGEN HEARTBEAT

The idea that telescopes could detect neutral hydrogen goes back to the 1940s, when Dutch astronomer Hendrik Christoffel van de Hulst predicted that hydrogen atoms can spontaneously emit pulses of electromagnetic radiation. This happens because each atom of hydrogen can flip between two energy states, emitting or absorbing radiation at a wavelength of 21 centimeters (or a frequency of 1,420 megahertz). Such emissions are the "heartbeat" of hydrogen and can add up to detectable signals when clouds of the gas accumulate on cosmic scales.

Such signals should have first emerged about 380,000 years after the big bang, when the universe cooled enough for protons and electrons that previously filled space to coalesce into atoms of hydrogen. Besides forming the raw material from which all subsequent objects would arise, this event had the added benefit of making the universe transparent rather than opaque, liberating the fossil radiation produced by the big bang to stream through the cosmos. We now see this radiation—the big bang's afterglow—as the cosmic microwave background (CMB). Thereafter, neutral hydrogen pervaded the dark universe for perhaps the first few hundred million years, until the break of cosmic dawn, when the first stars and galaxies began to shine.

Cosmologists are particularly interested in the dark ages because they offer a glimpse of the universe when it was relatively pristine, free of confounding astrophysical effects. Back then, the distribution of neutral hydrogen still carried the imprints of primordial quantum fluctuations that had been profoundly magnified by the universe's rapid expansion in the first fractions of a second of its history—unsullied by the emergence of stars, galaxies and galaxy clusters. It is possible that the 21-centimeter signals from the dark ages could carry indications of new physics or deviations from the standard

model of cosmology. "It's a playground for testing cosmology," Burns says.

The first radio telescopes on and above the far side of the moon will be simple. They will gather hints of this shadowy slice of otherwise unseen cosmic time. As more sophisticated instrumentation comes online, the 21-cm signals will emerge in richer detail, allowing astronomers to create dynamic, high-resolution maps of hydrogen clouds.

"The nice thing about neutral hydrogen is that it's not just a snapshot in time like the CMB," says Kristian Zarb Adami of the University of Oxford. By tracking the fluctuating 21-cm signal over cosmic time, telescopes can chart the evolution of the early universe through the dark ages all the way up to the cosmic dawn and even beyond. After the dawn came the epoch of reionization, when the radiation from the first massive stars and other violent astrophysical phenomena sufficiently reheated the remaining neutral hydrogen to transform it back to plasma. That epoch ultimately extinguished the 21-cm signals.

FAR-SIDE PIONEERS

Some pathfinder instruments are already in operation. They are part of China's Chang'e-4 lander on the moon's far side, as well as a lunar orbiter named Queqiao ("Magpie Bridge"), which relays signals from the lander to Earth. Queqiao was launched in May 2018, and Chang'e-4 reached the lunar surface in January 2019. "This was the first time there was a soft landing on the far side of the moon," says Bernard Foing, executive director of the International Lunar Exploration Working Group and a planetary scientist at VU Amsterdam. "It was a great success."

Both Chang'e-4 and Queqiao carried radio antennas. But those on Queqiao, built in collaboration with Dutch scientists, did not extend completely, and Chang'e-4's single antenna is hindered by radio-frequency interference (RFI) coming from the lander's electronics. Future dark-age-surveying lunar spacecraft could include additional shielding to minimize RFI. They could also deploy multiple antennas across tens or hundreds of kilometers of lunar soil.

The next preparatory phase for far-side astronomy is set to begin with the launch of ROLSES (Radiowave Observations at the Lunar Surface of the photoElectron Sheath) this October. ROLSES will travel to the moon within a privately developed lander licensed by NASA as part of the space agency's Commercial Lunar Payload Services program. Although it will touch down in the Oceanus Procellarum region on the moon's near side, ROLSES's task of characterizing the RFI generated by lunar soil is crucial for future work identifying other radio signals on the far side. "This is real," says Burns, who is a member of the ROLSES team. "I have been working on this for 35 years. It's actually happening."

Another mission to characterize the radio-frequency interference on the moon—the Lunar Surface Electromagnetics Experiment (LuSEE)—is slated to launch as early as 2024. "LuSEE is going to the far side," Burns says. "It's going to go to the Schrömdinger impact basin." The lander carrying LuSEE may also have another payload: DAPPER (Dark Ages Polarimeter Pathfinder), a telescope for detecting the 21-cm signal from the cosmic dark ages. "DAPPER was originally designed to be an orbiter around the moon, but it may go on this lander," Burns says. "NASA has funded us to work on the mission concept for DAPPER. We'll be ready to go."

Whether in orbit or on the lunar surface, DAPPER will be limited to a set of dipole antennas in one location. But astronomers have more ambitious plans for deploying arrays of antennas on the moon. These arrays, which combine signals from individual antennas spread over large distances, act as telescopes with resolutions far greater than would be possible with a single antenna and can effectively pinpoint sources in the sky.

THE ERA OF ARRAYS

Xuelei Chen of the National Astronomical Observatories at the Chinese Academy of Sciences thinks lunar orbit is the best near-term site for creating dark-age-mapping lunar arrays. Antennas on a number of satellites could be configured into an array that carries out observations when the satellites are all on the far side. "This is a small experiment with moderate cost, and we could accomplish it with current technology," Chen says.

The tentative plan calls for a fleet of five to eight satellites flying in carefully choreographed formation to form an array. One of the satellites would be a larger mother ship that would host most of the electronics for receiving and combining the signals from other satellites and then relaying the results to Earth. "We want to have them launched as an assemblage, and then they will be released one by one," Chen says.

Putting such an array on the far side's surface will be far more challenging for many reasons, among them the moon's rugged terrain and the spacecraft-threatening chill of the 14-day-long lunar night. To begin preparing for this type of mission, Foing's team is planning to test the deployment of radio antennas using robotic rovers designed by the German Aerospace Center. The test will occur in June on the flanks of Mount Etna, an active volcano in Sicily meant as a proxy for the lunar surface. Scientists will control the rovers remotely; each rover will carry four boxes of antennas. "We will position them in different configurations to show that we will be able to do that in the future on the moon," Foing says.

Another way of deploying a radio array on the moon's far side would be to simply drop antennas from an orbiter to land and unfurl where they may. Adami and his colleagues are working on one such idea: a low-frequency interferometer, designed to precisely measure characteristics of radio emissions, that involves 128 fractal-like "mini stations." Each station has eight arms, and each

arm combines 16 spiral antennas. “My idea would be that these fall off from the satellite and all land in different parts on the moon’s surface,” Adami says.

To minimize the number of moving parts, the team has figured out how to print these antennas as flat sheets that will take their final form after being rolled out on the lunar surface. “You could print antennas as fast as you print newspapers. We’ve been testing this technology for the past four or five years,” Adami says. “We are in the process of prototyping these spiral antennas.” The next step, he adds, is for the scientists to design a mini station and drop it from a drone in remote areas, such as an arid region of Western Australia, to see if it unfurls.

Meanwhile Burns is also leading a NASA-funded concept study for building another lunar radio telescope, aptly called FARSIDE (Farside Array for Radio Science Investigations of the Dark ages and Exoplanets). To design FARSIDE, Burns and co-principal investigator Gregg Hallinan of the California Institute of Technology have teamed up with NASA’s Jet Propulsion Laboratory. The scientists are looking to land a payload of four rovers and 256 antennas, totaling about 1.5 metric tons, using lunar landers funded by NASA. The rovers would deploy the antennas, spreading them in four flowerlike petals over a region that is 10 kilometers in diameter. “We can do this with current technology,” Burns says. “So this all looks very plausible [for] later in the decade.” SA

Astronomer Avi Loeb Says Aliens Have Visited, and He's Not Kidding

In conversation, the Harvard University professor explains his shocking hypothesis– and calls out what he sees as a crisis in science

By Lee Billings

Astrophysicist Avi Loeb at the unveiling of the Breakthrough Starshot initiative in New York City on April 12, 2016.

JEMAL COUNTESS *GETTY IMAGES*

Lee Billings is a senior editor for space and physics at *Scientific American.*

AVI LOEB IS NO STRANGER TO CONTROVERSY. THE PROLIFIC HARVARD University astrophysicist has produced pioneering and provocative research on black holes, gamma-ray bursts, the early universe and other standard topics of his field. But for more than a decade he has also courted a more contentious subject—namely, space aliens, including how to find them. Until relatively recently, Loeb's most high-profile work in that regard was his involvement with Breakthrough Starshot, a project funded by Silicon Valley billionaire Yuri Milner to send laser-boosted, gossamer-thin mirrorlike spacecraft called "light sails" on high-speed voyages to nearby stars. All that began to change in late 2017, however, when astronomers around the world scrambled to study an enigmatic interstellar visitor—the first ever seen—that briefly came within range of their telescopes.

The object's discoverers dubbed it 'Oumuamua—a Hawaiian term that roughly translates to "scout." The unavoidably cursory examinations of this celestial passerby showed it had several properties that defied easy natural explanation. 'Oumuamua's apparent shape—which was like a 100-meter-long cigar or pancake—did not closely resemble any known asteroid or comet. Neither did its brightness, which revealed 'Oumuamua was at least 10 times more reflective than one of our solar system's typical space rocks—shiny enough to suggest the gleam of burnished metal. Most strangely, as it zoomed off after swooping by the sun, the object sped up faster than could be explained by our star's waning gravitational grip alone. Run-of-the-mill comets can exhibit similar accelerations because of the rocketlike effect of evaporating gases jetting from their sunlight-warmed icy surfaces. But no signs of such jets were seen around 'Oumuamua.

To Loeb, the most plausible explanation was as obvious as it was sensational: taken together with its possibly pancakelike shape and high reflectivity, 'Oumuamua's anomalous acceleration made perfect sense if the object was in fact a light sail—perhaps a derelict from some long-expired galactic culture. Primed by years spent pondering how we might someday find evidence of cosmic civilizations in the sky's depths, he became increasingly convinced that, with 'Oumuamua, the evidence had instead found us. In late 2018 Loeb and his co-author Shmuel Bialy, a Harvard postdoctoral fellow, published a paper in the *Astrophysical Journal Letters* arguing that 'Oumuamua had been nothing less than humanity's first contact with an artifact of extraterrestrial intelligence.

The paper has been a smash hit with journalists but has fallen flat with most of Loeb's astrobiology-focused peers, who insist that, while strange, 'Oumuamua's properties still place it well within the realm of natural phenomena. To claim otherwise, Loeb's critics say, is cavalier at best and destructive at worst for the long struggle to remove the stigma of credulous UFO and alien-abduction reports from what should unquestionably be a legitimate field of scientific inquiry.

Loeb has now taken his case to the public with the book *Extraterrestrial: The First Sign of Intelligent Life beyond Earth*, which is just as much about the author's life story as it is about 'Oumuamua's fundamental mysteries. *Scientific American* spoke with Loeb about the book, his controversial hypothesis and why he believes science is in crisis.

[*An edited transcript of the interview follows.*]

Hi, Avi. How are you?

I'm good, but I have been losing sleep, because in order to cope with all the media requests, I've been doing interviews with, for example, *Good Morning Britain* at 1:50 A.M. and *Coast to Coast AM* at 3 A.M.—plus appearances on U.S. network and cable television. I've got about 100 podcast interviews to do in the next few weeks. And I already recorded long conversations with [podcasters] Lex Fridman and Joe Rogan for their shows. I've never seen anything like this; there has been so much interest in the book. I mean, there were 10 filmmakers and producers from Hollywood who contacted

me over the past few weeks! I joked with my literary agent that if a film comes out of this, I want to be played by Brad Pitt.

Hah, indeed, the resemblance is uncanny. Based on your productivity, I've never gotten the sense that you get a lot of sleep anyway.

My routine is to wake up each morning at 5 A.M. and go jogging. It's really beautiful when nobody's outside—just me and the birds, ducks and rabbits. And, yes, because of the pandemic, the past 10 months have been the most productive in my career. I don't need to commute to work. I don't need to meet so many people. And most important, I don't need to think about what's wrong with all the things that other people say!

Speaking of important things, here is one I think we both agree on: in science, we must keep each other honest. I mention it only because there's a point in* Extraterrestrial *where you claim you don't want the limelight and that you're not interested in self-promotion. How can that be true?

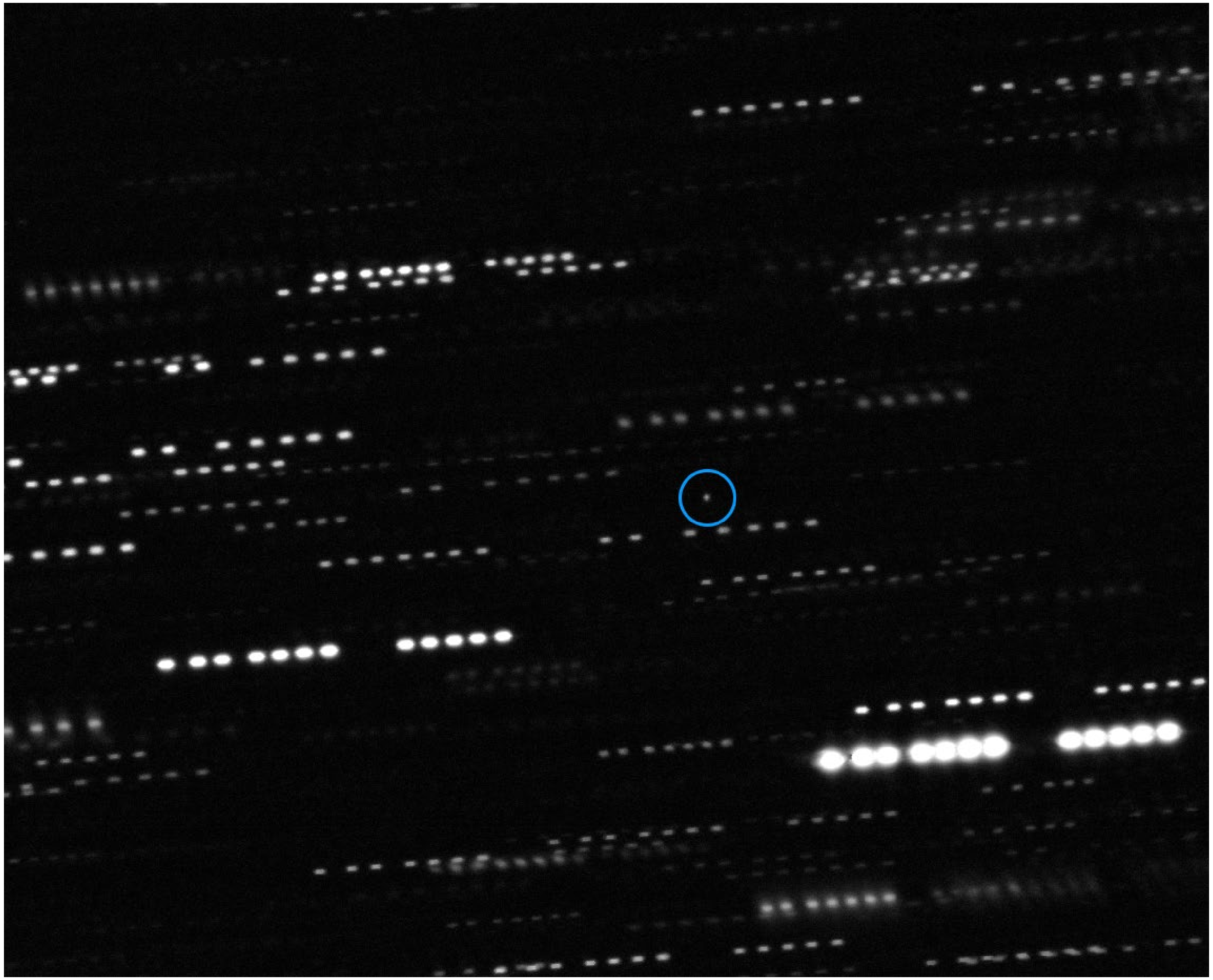
Let me explain. I think talking to the media is an important opportunity because it allows me to share my message with a broader audience that otherwise would not have exposure to it.

What is your message, exactly? I take it you're talking about more than 'Oumuamua.

Yes. My message is that something is wrong with the scientific community today in terms of its health.

Too many scientists are now mostly motivated by ego, by getting honors and awards, by showing their colleagues how smart they are. They treat science as a monologue about themselves rather than a dialogue with nature. They build echo chambers using students and postdocs who repeat their mantras so that their voice will be louder and their image will be promoted. But that's not the purpose of science. Science is not about us; it's not about empowering ourselves or making our image great. It's about trying to understand the world, and it's meant to be a learning experience in which we take risks and make mistakes along the way. You can never tell in advance, when you work on the frontier, what is the right path forward. You only learn that by getting feedback from experiments.

Which is the other problem with science today: peo-



Marked with a blue circle, 'Oumuamua appears as a faint dot in the center of this image, which is one of the best available and combines observations from multiple different telescopes.

ESO/K. MEECH ET AL.

ple are not only motivated by the wrong reasons; they are also no longer guided by evidence. Evidence keeps you modest because you predict something, you test it, and the evidence sometimes shows you're wrong. Right now you have many celebrated scientists doing mathematical gymnastics about lots of untestable things: string theory, the multiverse, even the theory of cosmic inflation. Once, in a public forum, I asked [physicist] Alan Guth, who originated the theory, "Is inflation falsifiable?" And he said it's a silly question, because for whatever cosmological data an experiment gives us, a model of inflation can be found that accommodates it. And therefore, inflation is in a very strong position because it can explain anything! But I see this as a very weak position because a theory of everything is sometimes a theory of nothing. There may be no difference between the two.

To me, this bubble of imaginary stuff is like being high on drugs: You can get high and imagine that you're wealthier than Elon Musk, who is now the richest person in the world. That's a very fun thought. You can feel really good about it and talk about it with your friends. And if you're part of a big like-minded community, everyone can support and respect one another, and you give one another awards, and that's great, right? But then if you go to withdraw funds, if you want to really spend that money you think you have, you realize that you don't actually have anything. Just like going to an ATM, doing experiments can serve as a reality check. And in science, it's essential that we have that check—that we make testable predictions and put some skin in the game—because otherwise we won't learn anything new. I don't think that's properly recognized anymore.

> **"There are, of course, science-fiction stories about aliens, and there are many unsubstantiated UFO reports. Now, suppose there was some literature about the magical properties of COVID-19 that had no bearing in reality. Would that mean scientists should never work on finding a vaccine to this pandemic? No! I don't see the search for technological signatures any differently from the search for the nature of dark matter."**
> ***—Avi Loeb***

So speculating about string theory and multiverses is bad, but speculating about alien civilizations and their artifacts passing through the solar system is okay? You could say appealing to "aliens" can explain anything, too.

The difference is: you can make predictions and test for the latter, and the speculations come from a conservative position.

If 'Oumuamua is a member of a population of objects moving on random trajectories, then based on its discovery with the Pan-STARRS telescope, you can estimate that we should very soon begin finding, on average, one of these objects per month after the Vera C. Rubin Observatory comes online. We can also establish a system of instruments—satellites, maybe—that would not only monitor the sky but also be able to react to the approach of such objects so we can get photographs of them as they come in rather than chasing them as they go out, because they move very fast. Not all this work needs to be in space, either: You can imagine meteors of interstellar origin as well, and we can search for those. And if you find any that ended up on Earth's surface, you might even be able to examine them with your own hands.

People ask why I get this media attention. The only reason is because my colleagues are not using common sense. Contrast string theory and multiverses with what I and many others say, which is that based on the data from NASA's Kepler mission, roughly half of the galaxy's sunlike stars have a planet about the size of Earth, at about the same distance of Earth from the sun, so that you can have liquid water on the surface and the chemistry of life as we know it. So if you roll the dice on life billions of times in the Milky Way, what is the chance that we are alone? Minuscule, most likely! To say that if you arrange for similar circumstances, you get similar outcomes is, to me, the most conservative statement imaginable. So I would expect most people to endorse that, to hug me and say, "Great, Avi, you're correct. We should look for these things because they must be very likely." Instead what I see is a backlash that shows a loss of an intellectual compass—because how else can you explain working on string theory's extra dimensions or the multiverse when we have no clue for their existence? But that is considered mainstream? That's crazy.

Allow me to put this in a very specific context. I'm obviously not a rebel outsider; I'm in leadership positions. I chair the Board on Physics and Astronomy of the National Academies [of Sciences, Engineering, and Medicine], okay? That board is overseeing the Astronomy and Astrophysics Decadal Survey, which will set major science priorities for NASA and the [National Science Foundation] when it is released later this year. Now, I see astronomers

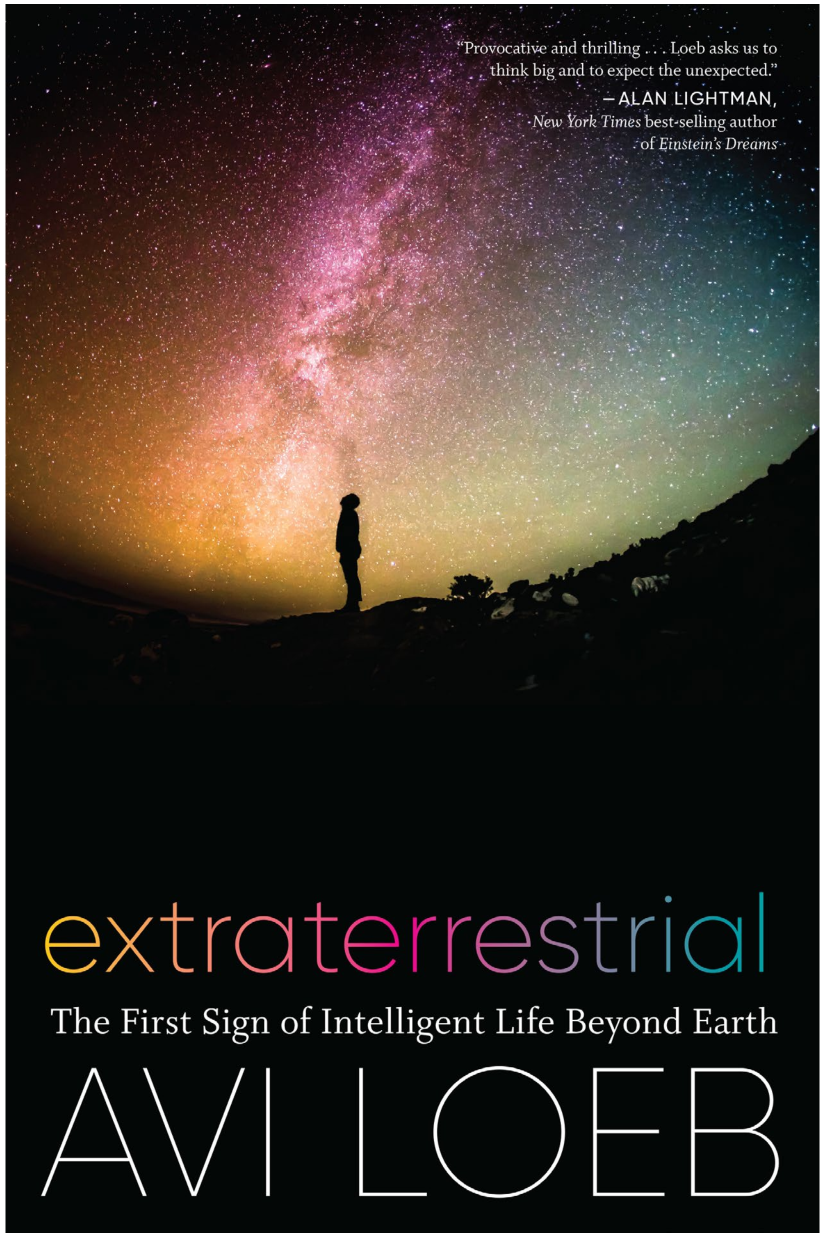
talking about future telescopes costing billions of dollars, with the main motivation being to find life by looking for oxygen in the atmospheres of exoplanets. That is a noble wish. But if you look at Earth for its first two billion years or so, the planet did not have much oxygen in its atmosphere even though it had a lot of microbial life. That's point number one. Point number two is that even if you have oxygen, you can get it from natural processes such as breaking apart water molecules. So even if you spend these billions and find oxygen and maybe even find methane along with it, people will still argue about it forever. Look at how much discussion there has been about the potential detection of phosphine on Venus, which is a very unusual molecule, compared with oxygen. Anyway, my point is that with these same instruments—you don't need any extra investment of funds—you can actually get conclusive evidence for life, intelligence and technology. What would that be? Industrial pollution in the same atmosphere. You could, for instance, look for chlorofluorocarbons, these complex molecules only produced on Earth for refrigeration systems. If you found that on another planet, there is just no way nature would produce these molecules naturally. You would have conclusive evidence that life—and more—existed there.

So what is the problem with saying that looking for industrial pollution is a worthwhile thing to do? What other than some sort of psychological barrier that prevents some scientists from admitting they want the search for technological signatures of alien civilizations to be at the periphery, with very little funding? What I'm saying is that these sorts of things should be prioritized and that they are conservative things to do because they will bring us the most information about the existence of alien life. And yet the opposite is being done right now.

You write about a concept you call "'Oumuamua's wager," after Pascal's wager, 17th-century mathematician Blaise Pascal's argument that the benefits of assuming God exists outweigh the drawbacks. Similarly, you say believing 'Oumuamua is an alien artifact would be a net good because it could catalyze a revolution in space science and technology centered on a more vigorous search for life and intelligence beyond Earth. Even if that hunt finds no aliens, your reasoning goes, we'd still gain a much deeper understanding of our cosmic context. And the investments behind it would enhance our ability to answer other questions about the universe and perhaps even help stave off our own extinction. But if the stakes are so high, what about the counterargument that going "all in" on promoting 'Oumuamua's putative artificial nature is reckless and dangerous? Your critics say you are doing more harm than good. For instance, you mentioned you appeared on Joe Rogan's podcast, one of the most popular in the world. That's great for selling books. But given Rogan's reputation for spreading dangerous misinformation on his podcast, is that sort of thing a wise move? Would you also agree to be a speaker at a gathering of UFO "true believers" outside Area 51? Where do you draw the line for public outreach that risks enhancing the so-called giggle factor that has stymied progress in the search for extraterrestrial intelligence [SETI] for decades?

Okay, here is my point of view. By and large, the public funds science. And the public is extremely interested in the search for alien life. So I must ask: If scientists are supported by the public, how dare they shy away from this question that can be addressed with the technologies they are developing?

There are, of course, science-fiction stories about aliens, and there are many unsubstantiated UFO reports. Now,



HOUGHTON MIFFLIN HARCOURT

suppose there was some literature about the magical properties of COVID-19 that had no bearing in reality. Would that mean scientists should never work on finding a vaccine to this pandemic? No! I don't see the search for technological signatures any differently from the search for the nature of dark matter. We have invested hundreds of millions of dollars in searching for weakly interacting massive particles, a leading dark matter candidate. And so far those searches have failed. That doesn't mean they were a waste: going down dark alleys is part of the scientific process.

And in terms of risk, in science, we are supposed to put everything on the table. We cannot just avoid certain ideas because we worry about the consequences of discussing them, because there is great risk in that, too. That would be similar to telling Galileo not to speak about Earth moving around the sun and to avoid looking in his telescope because it was dangerous to the philosophy of the day. We should not want to repeat that experience. We need an open dialogue among scientists where people present different ideas and then allow evidence to dictate which one is right. In the context of ‘Oumuamua, I say the available evidence suggests this particular object is artificial, and the way to test this is to find more [examples] of the same and examine them. It's as simple as that.

So how do you change this situation? I think the answer is to bring it to the public as much as I can.

In your book, you link your outspokenness about ‘Oumuamua with a phrase, an ethos, you learned when you were a conscript in the Israel Defense Forces: "To lay your body on the barbed wire." That is, to make personal sacrifices for the greater good. Are you to be a martyr for this cause, then? Have you lost friends or stature over it?

No one has violently assaulted me or anything like that. Maybe people talk behind my back, which would make more sense, given my leadership positions. But I don't really know. I have zero footprint on social media. Although I should say that I think my critics who are most vocal with nasty remarks on Twitter and elsewhere are relatively mediocre scientists. Most really good scientists would not behave that way—they would make arguments for or against my claims, and that would be enough. Nasty remarks don't make sense—except, well, deep inside, I would not be surprised if many of these critics are actually quite intrigued by this possibility that ‘Oumuamua is artificial. But they don't want to admit it. So they loudly say the opposite.

Unfortunately, my situation is different from that of the young postdocs who I've worked with because they need to apply for jobs. I'm sure that people have approached them and said, "Look, this is dangerous for you." And so they froze and basically stopped working on anything related. This isn't surprising. If you create a hostile intellectual culture where something like SETI is not being honored, then young, bright people will not go there. But don't step on the grass and then complain it doesn't grow as you stand on it. Don't block brilliant researchers from working on SETI and then say, "Look, nothing is being found. SETI is a failure!"

None of this means all of space science should be about SETI. If you look at the commercial world, companies such as Bell Labs in the past or Google now, they incentivize and allow for their personnel to pursue innovative "blue sky" research that is not immediately applicable for profit. But if you look at academia, it's much more conservative than the commercial sector. That doesn't make sense.

How do you respond to the idea that for a person with a hammer, everything looks like a nail? Someone could uncharitably say what you are really doing here is attempting to curry further favor with wealthy benefactors, such as Yuri Milner, because you are an adviser for his Breakthrough Initiatives programs, which fund research related to SETI and light sails.

It's true for me—and everyone else, I think—that my imagination is limited by what I know. I can't deny the fact that my involvement in Breakthrough was influential here. I was the one who suggested the light sail [proposed by physicist Philip Lubin] to Yuri Milner as a promising concept for interstellar spacecraft in the first place. So I had it in my vocabulary, and as a result of that, I imagined it as applied to ‘Oumuamua. Now, you might ask, "Okay, well, isn't that a biased view?" I would say this occurs again and again in physics and in SETI. In the context of SETI, you know, once we developed radio technology, we started searching the sky looking for radio signals. It was the same for lasers. It's just natural that once you work on some technology that you imagine maybe it exists out there and search for it. So I would not deny that the reason the light sail idea was in my brain is because I had previously worked on it, yeah. But in terms of trying to motivate Yuri, that has nothing to do with it. Why would I do it this way when I can just approach him directly whenever I want to advocate my views? And it is not as if my work on ‘Oumuamua was coordinated with or supported by Breakthrough Initiatives. They have issued no press releases about my ideas. If anything, they might be worried—they have their own reputation to preserve and so forth. On this issue, I've had zero support from or communication with them. This was me being curious, not using ‘Oumuamua as some sort of a political vehicle in the context of Breakthrough. That has nothing to do with my motivation.

After this, what comes next for you? Do you have plans?

I just stepped down from being chair of Harvard's astronomy department, so I really do have the ability now to move to the next phase. And the question is: What would it be? Life, of course, is not always what you've planned, but another leadership opportunity would be so tempting because I could try to shape reality in a way others would not. I couldn't pass that up. But maybe we should exclude leadership possibilities from this. Maybe I won't be offered anything again because of my ideas about ‘Oumuamua! That's a possibility. Then I'd write more books, do more research and continue to jog every morning. SA

Caleb A. Scharf is director of astrobiology at Columbia University. He is author and co-author of more than 100 scientific research articles in astronomy and astrophysics. His work has been featured in publications such as *New Scientist, Scientific American, Science News, Cosmos Magazine, Physics Today* and *National Geographic.* For many years he wrote the Life, Unbounded blog for *Scientific American.*

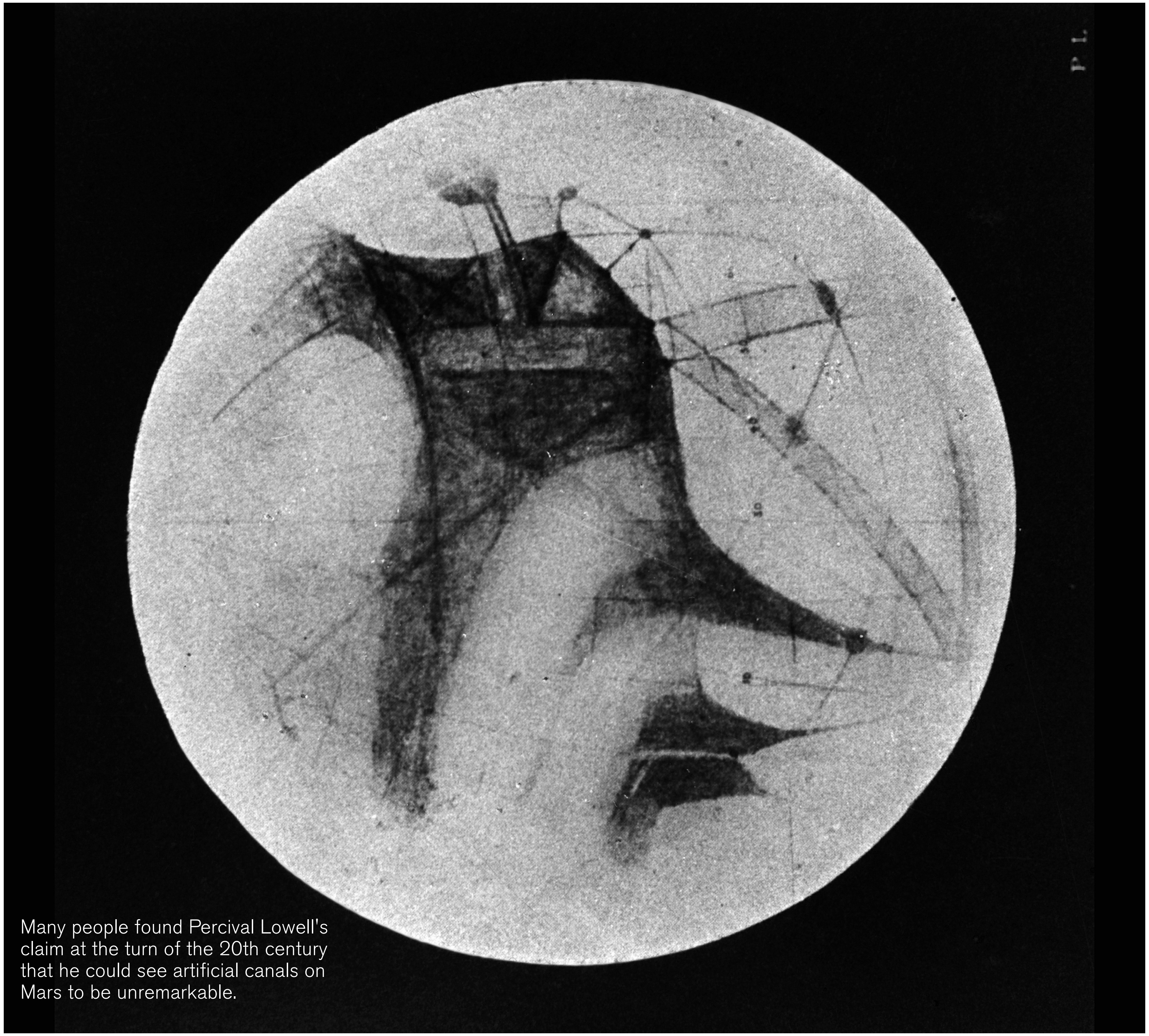
SPACE

Until Recently, People Accepted the "Fact" of Aliens in the Solar System

For centuries, right up until the 1960s, the notion of life on Mars—and elsewhere—wasn't considered especially remarkable

One of the most intriguing aspects of the history of the human quest to discover whether or not there is other life in the universe, and whether any of it is recognizably intelligent in the way that we are, is just how much our philosophical mood has changed back and forth across the centuries.

Today we're witnessing a bit of a "golden age" in terms of active work toward answers. Much of that work stems from the overlapping revolutions in exoplanetary science and solar system exploration, and our ongoing revelations about the sheer diversity and tenacity of life here on Earth. Together these areas of study have given us



Many people found Percival Lowell's claim at the turn of the 20th century that he could see artificial canals on Mars to be unremarkable.

GETTY IMAGES

places to look, phenomena to look for, and increased confidence that we're quickly approaching the point where our technical prowess may cross the necessary threshold for finding some answers about life elsewhere.

Into that mix goes the search for extraterrestrial intelligence (SETI), as we've become more comfortable with the notion that the technological restructuring and repurposing of matter is something we can, and should, be actively looking for. If for no other reason than our own repurposing of matter, here on Earth, has become ever more vivid and fraught and therefore critical to appreciate and modify in aid of long-term survival. But this search, labeled as both SETI and the quest for "technosignatures," still faces some daunting challenges–not least the catch-up required after decades of receiving a less than stellar allocation of scientific resources.

What is so fascinating is that in many respects we have already been here and done all of this before, just not recently and not with the same set of tools that we now have in hand.

In western Europe, during the period from some 400 years ago until the past century, the question of life beyond Earth seems to have been less of "if" and more of "what." Famous scientists such as Christiaan Huygens wrote in his *Cosmotheoros* of "So many Suns, so many Earths, and every one of them stock'd with so many Herbs, Trees and Animals … even the little Gentlemen round Jupiter and Saturn …" And this sense of cosmic plurality wasn't uncommon. It was in almost all respects far simpler and more reasonable to assume that the wealth of life on Earth was simply repeated elsewhere. That is once one let go of a sense of earthly uniqueness.

In other words, in many quarters there was no "Are we alone?" question being asked; instead the debate was already onto the details of how the life elsewhere in the cosmos went about its business.

In the 1700s and 1800s we had astronomers like William Herschel or the more amateur Thomas Dick not only proposing that our solar system, from the moon to the outer planets, was overrun with life-forms (Dick holding the record by suggesting that Saturn's rings held around eight trillion individuals) but convincing themselves that they could see the evidence. Herschel, with his good telescopes, becoming convinced there were forests on the moon, in the *Mare humorum*, and speculating that the sun's dark spots were actually holes in a glowing hot atmosphere, beneath which a cool surface supported large alien beings.

Even though we might question some of their scientific standards, people such as Herschel and Dick were indeed following the philosophy of life being everywhere and elevating it to the level of any other observable phenomenon. Herschel was also applying the best scientific instruments he could at the time.

All the way into the 20th century, prior to the data obtained by the Mariner 4 flyby in 1965, the possibility that Mars had a more clement surface environment, and therefore life, still carried significant weight. Although there had been extreme claims like Percival Lowell's "canals" on Mars in the late 1800s and very early 1900s, astronomers of the time largely disagreed with these specific interpretations. Interestingly, that was because they simply couldn't reproduce the observations, finding the markings he associated with canals and civilizations to be largely nonexistent (an example of how better data can discount pet theories). But aside from Lowell's distractions, the existence of a temperate climate of sorts on Mars was not easy to discount, nor was life on its surface. For example, Carl Sagan and Paul Swan published a paper just ahead of Mariner 4's arrival at Mars in which they wrote:

"The present body of scientific evidence suggests, but does not unambiguously demonstrate, the existence of life on Mars. In particular, the photometrically observed waves of darkening which proceed from the vaporizing polar caps through the dark areas of the Martian surface have been interpreted in terms of seasonal biological activity."

Suffice to say, this proposal went the way of many other overly optimistic ideas about finding life on the Red Planet. Although it is fascinating how well the periodic darkening phenomenon they discussed could indeed fit into a picture of a surface biosphere on Mars–and remains perhaps a rather sobering lesson in overinterpreting limited data.

But the key point is that we have actually more often than not been of a mindset that life is out there and could explain certain cosmic observations. The problem has been that as data have improved and scrutiny has intensified, the presence of life has not revealed itself–from planetary

exploration or from the search for extraterrestrial intelligence. And because of that we've swung to the other extreme, where the question has gone from "what" all the way back to "if."

Of course, we have also likely systematically underestimated the challenge across the centuries. Even today it is apparent that the search for structured radio emissions from technological life has thus far only scratched the surface of a complex parameter space; a fact beautifully quantified and articulated by Jason Wright and his colleagues in 2018, as being much like looking in a hot tub of water to draw conclusions about the contents of Earth's oceans.

In that sense, perhaps the more fundamental question is whether or not we are, this time, technologically equipped to crack the puzzle once and for all. There is little doubt that our capacity to sense the most ethereal, fleeting phenomena in the cosmos is at an all-time high. But there seems to be a fine line between acknowledging that exciting possibility and falling prey to the kind of hubris that some of our precursors fell prey to. Naturally, we say, this is the most special time in human existence—if we can only expand our minds and our efforts, then all may be revealed!

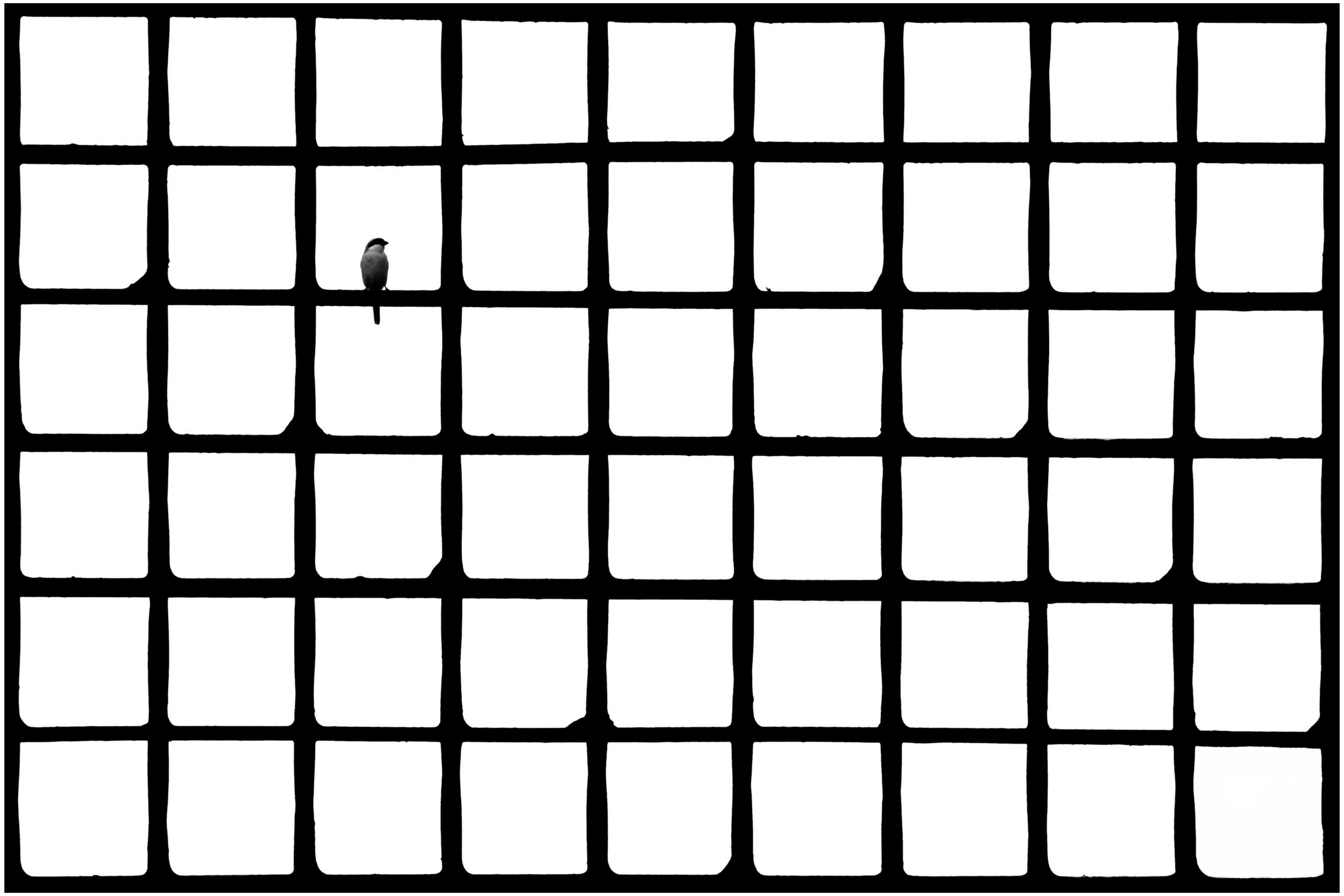
Of course, none of us can know for sure which way this will all go. We might do better being very explicit about the uncertainty inherent in all of this, because it's actually incredibly exciting to have to face the unknown and unknowable. What we shouldn't do is allow the unpredictable nature of this particular pendulum, swinging between possibilities, to dissuade us from trying.

John Horgan directs the Center for Science Writings at the Stevens Institute of Technology. His books include *The End of Science, The End of War and Mind-Body Problems* (available for free at mindbodyproblems.com). For many years, he wrote the immensely popular blog Cross Check for *Scientific American.*

MATH

Quantum Mechanics, Free Will and the Game of Life

Some thoughts triggered by the death of mathematician John Conway



GETTY IMAGES

Before I get to the serious stuff, a quick story about John Conway, a.k.a. the "mathematical magician." I met him in 1993 in Princeton while working on "The Death of Proof." When I poked my head into his office, Conway was sitting with his back to me staring at a computer. Hair tumbled down his back; his sagging pants exposed his ass cleft. His office overflowed with books, journals, food wrappers and paper polyhedrons, many dangling from the ceiling. When I tentatively announced myself, he yelled without turning, What's your birthday! Uh, June 23, I said. Year! Conway shouted. Year! 1953, I replied. After a split second he blurted out, Tuesday! He tapped his keyboard, stared at the screen and exulted, Yes! Finally facing me, Conway explained that he belongs to a group of people who calculate the day of the week of any date, past or present, as quickly as possible. He, Conway informed me with a manic grin, is one of the world's fastest day-of-the-week calculators.

This encounter came back to me recently as I read a wonderful *New York Times* tribute to Conway, felled by COVID-19 last year at the age of 82. The *Times* focuses on the enduring influence of the Game of Life, a cellular automaton invented by Conway more than a half century ago. *Scientific American*'s legendary math columnist Martin Gardner introduced the Game of Life, sometimes just called Life, to the world in 1970 after receiving a letter about it from Conway. The

Times riff on Life got me thinking anew about old riddles. Like, Does free will exist?

Some background. A cellular automaton is a grid of cells whose states depend on the states of neighboring cells, as determined by preset rules. The Game of Life is a two-dimensional cellular automaton with square cells that can be in one of two states, alive or dead (often represented by black or white). *A given cell's state depends on the state of its eight immediate neighbors. A dead cell comes to life if three of its neighbors are alive, and a live cell stays alive if two or three of its neighbors are alive. Otherwise, the cell dies or remains dead. So simple!* And yet Life, when the rules are applied over and over, ideally by a computer, yields endlessly varied patterns, including quasianimated clusters of cells known as "longboats," "gliders," "spaceships" and my favorite, "Speed Demonoids."

Like the Mandelbrot set, the famous fractal icon, the Game of Life inspired the fields of chaos and complexity, which are so similar that I lump them together under a single term: chaoplexity. Chaoplexologists assume that just as Life's odd digital fauna and flora stem from straightforward rules, so do many real-world things. With the help of computer simulations, chaoplexologists hoped to discover the rules, or algorithms, underpinning stuff that has long resisted conventional scientific analysis, from immune systems and brains to stock markets and whole civilizations. (The "big data" movement has recycled the hope, and hype, of chaoplexology.)

Of course, the Game of Life can be interpreted in different ways. It resembles a digital, animated Rorschach test upon which scholars project their biases. For example, philosopher Daniel Dennett, commenting on Conway's invention in the *Times*, points out that Life's "higher-order patterns" emerge from processes that are "completely unmysterious and explicable.... No psionic fields, no morphic resonances, no élan vital, no dualism."

Dennett's comment annoyed me at first; Life just gives him an excuse to reiterate his defense of hard-core materialism. But Life, Dennett goes on to say, shows that deterministic rules can generate "complex adaptively appropriate structures" capable of "action" and "control." Yes! I thought, my own bias coming into play. Dennett clearly means that deterministic processes can spawn phenomena that transcend determinism, like minds with free will.

Then another thought occurred to me, inspired by my ongoing effort to understand quantum mechanics. Conventional cellular automata, including Life, are strictly local, in the sense that what happens in one cell depends on what happens in its neighboring cells. But quantum mechanics suggests that nature seethes with nonlocal "spooky actions." Remote, apparently disconnected things can be "entangled," influencing each other in mysterious ways, as if via the filaments of ghostly, hyperdimensional cobwebs.

I wondered: Can cellular automata incorporate nonlocal entanglements? And if so, might these cellular automata provide even more support for free will than the Game of Life? Google gave me tentative answers. Yes, researchers have created many cellular automata that incorporate quantum effects, including nonlocality. There are even quantum versions of the Game of Life. But, predictably, experts disagree on whether nonlocal cellular automata bolster the case for free will.

One prominent explorer of quantum cellular automata, Nobel laureate Gerard 't Hooft, flatly rules out the possibility of free will. In his 2015 monograph *The Cellular Automaton Interpretation of Quantum Mechanics*, 't Hooft argues that some annoying features of quantum mechanics—notably its inability to specify precisely where an electron will be when we observe it—can be eliminated by reconfiguring the theory as a cellular automaton. 't Hooft's model assumes the existence of "hidden variables" underlying apparently random quantum behavior. His model leads him to a position called "superdeterminism," which eliminates (as far as I can tell; 't Hooft's arguments aren't easy for me to follow) any hope for free will. Our fates are fixed from the big bang on.

Another authority on cellular automata, Stephen Wolfram, creator of Mathematica and other popular mathematical programs, proposes that free will is possible. In his 2002 opus *A New Kind of Science*, Wolfram argues that cellular automata can solve many scientific and philosophical puzzles, including free will. He notes that many cellular automata, including the Game of Life, display the property of "computational irreducibility." That is, you cannot predict in advance what the cellular automata are going to do, you can only watch and see what happens. This unpredictability is compatible with free will, or so Wolfram suggests.

John Conway, Life's creator, also defended free will. In a 2009 paper, "The Strong Free Will Theorem," Conway and Simon Kochen argue that quantum mechanics, plus relativity, provide grounds for belief in free will. At the heart of their argument is a thought experiment in which physicists measure the spin of particles. According to Conway and Kochen, the physicists are free to measure the particles in dozens of ways, which are not dictated by the preceding state of the universe. Similarly, the particles' spin, as measured by the physicists, is not predetermined.

Their analysis leads Conway and Kochen to conclude that the physicists possess free will—and so do the particles they are measuring. "Our provocative ascription of free will to elementary particles is deliberate," Conway and Kochen write, "since our theorem asserts that if experimenters have a certain freedom, then particles have exactly the same kind of freedom." That last part, which ascribes free will to particles, threw me at first; it sounded too woo. Then I recalled that prominent scientists are advocating panpsychism, the idea that consciousness pervades all matter, not just brains. If we grant electrons consciousness, why not give them free will, too?

To be honest, I have a problem with all these treatments of free will, pro and con. They examine free will within the narrow, reductionistic framework of physics and mathematics, and they equate free will with randomness and unpredictability. My choices, at least important ones, are not random, and they are all too predictable, at least for those who know me.

For example, here I am arguing for free will once again. I do so not because physical processes in my brain compel me to do so. I defend free will because the idea of free will matters to me, and I want it to matter to others. I am committed to free will for philosophical, ethical and even political reasons. I believe, for example, that deterministic views of human nature make us more likely to accept sexism, racism and militarism. No physics model—not even the most complex, nonlocal cellular automaton—can capture my rational and, yes, emotional motives for believing in free will, but that doesn't mean these motives lack causal power.

Just as it cannot prove or disprove God's existence, science will never decisively confirm or deny free will. In fact, 't Hooft might be right. I might be just a mortal, 3-D, analog version of the Speed Demonoid, plodding from square to square, my thoughts and actions dictated by hidden, superdeterministic rules far beyond my ken. But I can't accept that grim worldview. Without free will, life lacks meaning and hope. Especially in dark times, my faith in free will consoles me and makes me feel less bullied by the deadly Game of Life.

Avi Loeb is former chair (2011–2020) of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project and is a member of President's Council of Advisors on Science and Technology. Loeb is author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*.

SPACE

Did a Supermassive Black Hole Influence the Evolution of Life on Earth?

The idea isn't as absurd as it might sound

MARK GARLICK GETTY IMAGES

In 1939 Albert Einstein published a paper in *Annals of Mathematics*, arguing that black holes do not exist in nature. A quarter of a century later Maarten Schmidt discovered quasars as powerful sources of light at cosmological distances. These enigmatic pointlike sources were explained in the mid-1960s by Yakov Zel'dovich in the East and Ed Salpeter in the West as supermassive black holes that are fed with gas from their host galaxies. When gas flows toward the black hole, it swirls like water going down the drain.

As the gas approaches a fraction of the speed of light at the innermost stable circular orbit (ISCO) around the black hole, it heats up by

rubbing against itself through turbulent viscosity.

Consequently, its accretion disk glows brightly, radiating away about a tenth of its rest mass and exceeding by orders of magnitude the total luminosity from stars in its host galaxy. High feeding rates make quasars visible all the way out to the edge of the visible universe. Decades later astronomers found that almost every galaxy hosts a supermassive black hole at its center, which is starved most of the time but bursts sporadically for merely tens of millions of years during each burst. The quasars resemble a baby that tends to remove food off the dining table as soon as it is fed by virtue of becoming too energetic.

In 2020 the Nobel Prize in Physics was awarded to Andrea Ghez and Reinhard Genzel for providing conclusive evidence that a black hole, albeit starved at the present time, lurks also at the center of our own Milky Way galaxy. This monster, weighing four million suns, is dormant right now, glowing as the feeble radio source Sagittarius A* (abbreviated SgrA*), which is a billion times fainter than it would have been if it was fed as generously as a quasar.

Even though SgrA* is dim right now, we have clues that it must have experienced episodes of vigorous feeding in the past. This is not a surprise, given that a gas cloud approaching the galactic center or a star passing within 10 times the horizon scale of SgrA* (which translates to roughly the Earth-sun separation), would get spaghettified by the strong gravitational tide there and turn into a stream of gas that triggers a quasarlike flare.

The "smoking gun" evidence for recent feeding episodes of SgrA* by massive quantities of gas is that young stars around SgrA* orbit in preferred planes. This implies that these stars formed out of planar gas disks, just like the planets in the solar system plane or the stars in the Milky Way disk. Because the age of the stars near SgrA* is less than a percent of the age of the Milky Way galaxy, major accretion episodes from disruption of gas clouds must have occurred at least 100 times around SgrA*, based on the Copernican principle that the present time is not special. Indeed, a pair of giant blobs of hot gas, called the Fermi bubbles, are observed to emanate from the galactic center along the rotation axis of the Milky Way, implying a recent accretion episode around SgrA* that could have powered them.

Theoretical calculations imply that in addition to disruption of massive gas clouds, individual stars are also scattered into the vicinity of the black hole and get tidally disrupted once every 10,000 years. The intense feeding from the resulting debris streams could lead to the brightest flares from SgrA*. Such tidal disruption events of stars are in fact observed in other galaxies at the expected rate.

Would the resulting flares of SgrA* have any implications for life on Earth? In principle, they could because they carry damaging x-ray and ultraviolet (XUV) radiation. In collaboration with my former postdoc, John Forbes, we showed in 2018 that the XUV radiation emitted during such flares would have the capacity to evaporate the atmosphere of Mars or Earth if the solar system had only been10 times closer to the center of the Milky Way. But even at larger distances, the XUV radiation could suppress the growth of complex life, creating an effect similar to stepping on a lawn so frequently that you inhibited its growth.

At the current location of the sun, terrestrial life is safe from XUV flares of SgrA*. Recent studies indicate, however, that the birthplace of the sun may have been significantly closer to the galactic center and that the sun migrated to its current location through gravitational kicks. The exposure to past XUV flares from SgrA* at closer distances could have harmed complex life during the early evolution of Earth. This might explain why the oxygen level in Earth's atmosphere rose to its currently high level only after two billion years, perhaps only after Earth was sufficiently far away from SgrA*. In collaboration with Manasvi Lingam, I am currently exploring this possible connection between terrestrial life and the migration of the sun away from the galactic center.

Traditionally, the sun was thought to be the only astronomical source of light that affected life on Earth. But it is also possible that the black hole SgrA* played an important role in shaping the history of terrestrial life. A surprising realization of this sort is similar to figuring out that a stranger might have impacted your family history before you were born. If a link between SgrA* and terrestrial life can be established, then this supermassive black hole might trigger a second Nobel Prize.

Ian Durham is a professor and chair of the physics department at St. Anselm College.
Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. His writing has appeared in *Nature News, Science News, Undark,* and elsewhere.
Karoline Wiesner is an associate professor in the School of Mathematics at the University of Bristol in England.

POLICY & ETHICS

Physicists Need to Be More Careful with How They Name Things

The popular term "quantum supremacy," which refers to quantum computers outperforming classical ones, is uncomfortably reminiscent of "white supremacy"

GETTY IMAGES

In 2012 quantum physicist John Preskill wrote, "We hope to hasten the day when well controlled quantum systems can perform tasks surpassing what can be done in the classical world." Less than a decade later two quantum computing systems have met that mark: Google's Sycamore and the University of Science and Technology of China's Jiǔzhāng. Both solved narrowly designed problems that are, so far as we know, impossible for classical computers to solve quickly. How quickly? How "impossible"? To solve a problem that took Jiǔzhāng 200 seconds, even the fastest supercomputers are estimated to take at least two billion years.

Describing what then may have seemed a

far-off goal, Preskill gave it a name: "quantum supremacy." In a blog post at the time, he explained "I'm not completely happy with this term, and would be glad if readers could suggest something better."

We're not happy with it either, and we believe that the physics community should be more careful with its language, for both social and scientific reasons. Even in the abstruse realms of matter and energy, language matters because physics is done by people.

The word "supremacy"—having "more power, authority or status than anyone else"—is closely linked to "white supremacy." This isn't supposition; it's fact. The Corpus of Contemporary American English finds "white supremacy" is 15 times more frequent than the next most commonly used two-word phrase, "judicial supremacy." Although English is the global lingua franca of science, it is notable that the USTC team avoided "quantum supremacy" because in Chinese, the character meaning "supremacy" also has uncomfortable, negative connotations. The problem is not confined merely to English.

White supremacist movements have grown around the globe in recent years, especially in the U.S., partly as a racist backlash to the Black Lives Matter movement. As Preskill has recently acknowledged, the word unavoidably "evokes a repugnant political stance."

"Quantum supremacy" has also become a buzzword in popular media (for example, here and here). Its suggestion of domination may have contributed to unjustified hype, such as the idea that quantum computers will soon make classical computers obsolete. Tamer alternatives such as "quantum advantage," "quantum computational supremacy" and even "quantum ascendancy" have been proposed, but none have managed to supplant Preskill's original term. More jargony proposals like "Noisy Intermediate Scale Quantum computing" (NISQ) and tongue-in-cheek suggestions like "quantum non-uselessness" have similarly failed to displace "supremacy."

Here we propose an alternative we believe succinctly captures the scientific implications with less hype and—crucially—no association with racism: quantum primacy.

What's in a name? It's not just that quantum supremacy by any other name would smell sweeter. By making the case for quantum primacy, we hope to illustrate some of the social and scientific issues at hand. In President Joe Biden's letter to his science adviser, biologist Eric Lander, he asks "How can we ensure that Americans of all backgrounds are drawn into both the creation and the rewards of science and technology?" One small change can be in the language we use. GitHub, for example, abandoned the odious "master/slave" terminology after pressure from activists.

Were physics, computer science and engineering more diverse, perhaps we would not still be having this discussion, which one of us wrote about four years ago. But in the U.S., when only 2 percent of bachelor's degrees in physics are awarded to Black students, when Latinos make up less than 7 percent of engineers, and women account for a mere 12 percent of full professors in physics, this is a conversation that needs to happen. As things stand, "quantum supremacy" can come across as adding insult to injury.

The nature of quantum computing and its broad interest to the public outside of industry laboratories and academia mean that the debate around "quantum supremacy" was inevitably going to be included in the broader culture war.

In 2019 a short correspondence to *Nature* argued that the quantum computing community should adopt different terminology to avoid "overtones of violence, neocolonialism and racism." Within days the dispute was picked up by the conservative editorial pages of the *Wall Street Journal*, which attacked "quantum wokeness" and suggested that changing the term would be a slippery slope all the way down to canceling Diana Ross' s "The Supremes."

Linguist Steven Pinker weighed in to argue that "the prissy banning of words by academics should be resisted. It dumbs down understanding of language: word meanings are conventions, not spells with magical powers, and all words have multiple senses, which are distinguished in context. Also, it makes academia a laughingstock, tars the innocent, and does nothing to combat actual racism & sexism."

It is true that "supremacy" is not a magic word, that its meaning comes from convention, not conjurers. But the context of "quantum supremacy," which Pinker neglects, is that of a historically white, male-dominated discipline. Acknowledging this by seeking better language is a basic effort to be polite, not prissy.

Perhaps the most compelling argument raised in favor of "quantum supremacy" is that it could function to reclaim the word. Were "quantum supremacy" 15 times more common than "white supremacy," the shoe would be on the other foot. Arguments for reclamation, however, must account for who is doing the reclaiming. If the charge to take back "quantum supremacy" were led by Black scientists and other underrepresented minorities in physics, that would be one thing. No survey exists, but anecdotal evidence suggests this is decidedly not the case.

To replace "supremacy," we need to have a thoughtful conversation. Not any alternative will do, and there is genuinely tricky science at stake. Consider the implications of "quantum advantage." An advantage might be a stepladder that makes it easier to reach a high shelf or a small head start in a race. Some quantum algorithms are like this. Grover's search algorithm is only quadratically faster than its classical counterpart, so a quantum computer running Grover's algorithm might solve a problem that took classical computers 100 minutes in the square root of that time—10 minutes. Not bad! That's definitely an advantage, especially as runtimes get longer, but it doesn't compare to some quantum speedups.

Perhaps the most famous quantum speedup comes from Shor's algorithm, which can find the factors of numbers (for example, 5 and 3 are factors of 15) almost exponentially faster than the best classical algorithms. While classical computers are fine with small numbers, every digit takes a toll. For example, a classical computer might factor a 100-digit number in seconds, but a 1,000-digit number would take billions of years. A quantum computer running Shor's algorithm could do it in an hour.

When quantum computers can effectively do things that are impossible for classical computers, they have something much more than an advantage. We believe primacy captures much of this meaning. Primacy means "preeminent position" or "the condition of being first." Additionally, it shares a Latin root (*primus,* or "first") with mathematical terms such as prime and primality.

While quantum computers may be first to solve a specific problem, that does not imply they will dominate; we hope quantum primacy helps avoid the insinuation that classical computers will be obsolete. This is especially important because quantum primacy is a moving target. Classical computers and classical algorithms can and do improve, so quantum computers will have to get bigger and better to stay ahead.

These kinds of linguistic hot fixes do not reach even a bare minimum for diversifying science; the most important work involves hiring and retention and actual material changes to the scientific community to make it less white and male. But if opposition to improving the language of science is any indication about broader obstacles to diversifying it, this is a conversation we must have.

Physicists may prefer vacuums for calculation, but science does not occur in one. It is situated in the broader social and political landscape, one that both shapes and is shaped by the decisions of researchers.

SCIENTIFIC AMERICAN Space & Physics

LETTERS TO THE EDITOR:
Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562, 212-451-8200 or editors@sciam.com.
Letters may be edited for length and clarity.
We regret that we cannot answer each one.

HOW TO CONTACT US:
For Advertising Inquiries: Scientific American, 1 New York Plaza, Suite 4600, New York, NY 10004-1562, 212-451-8893, fax: 212-754-1138
For Subscription Inquiries: U.S. and Canada: 888-262-5144,
Outside North America: Scientific American, PO Box 5715, Harlan IA 51593, 515-248-7684, www.ScientificAmerican.com

For Permission to Copy or Reuse Material From Scientific American:
Permissions Department, Scientific American, 1 New York Plaza,
Suite 4600, New York, NY 10004-1562, 212-451-8546,
www.ScientificAmerican.com/permissions.
Please allow three to six weeks for processing.